FINAL REPORT

Preliminary Groundwater Flow Model
Dell City Area,
Hudspeth and Culberson Counties, Texas

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EXECUTIVE SUMMARY

ES 1.0 Background and Previous Studies

The area surrounding Dell City in Hudspeth County, Texas (Figure ES-1) has been an important agricultural area since the late 1940s. Irrigation water is pumped from a fractured rock aquifer that extends north into New Mexico. Wells in the area can produce 3,000 gallons per minute (gpm) or more. Permian and Cretaceous limestones and basin fill of Quaternary age dominate the geology of the study area. The important aquifers in the area are Permian formations (The Bone Spring-Victorio Peak aquifer and the Capitan Reef aquifer). The older Bone Spring-Victorio Peak limestones were shelf deposits. The younger Capitan Reef was a barrier reef that encircled the Delaware Basin. The Salt Basin is a graben that is filled with alluvial sediments.

In recent years, the area has been considered to be a potential source of water supply for El Paso, located about 75 miles west of Dell City. The 2006 Regional Water Plan has identified properties currently owned by EPWU overlying the Capitan Reef Aquifer, and Dell City properties overlying the Bone Spring-Victorio Peak Aquifer that are not owned by EPWU for groundwater transfer beginning around 2030. These properties are shown in Figure ES-2.

Groundwater pumping in portions of the area is regulated by the Hudspeth County Underground Water Conservation District No. 1 and the Culberson County Groundwater Conservation District. Figure ES-3 presents the regulated areas of these districts in relation to the boundaries of the aquifers and the properties that may be involved in potential groundwater transfer projects. Outside of these districts, groundwater is regulated by the Rule of Capture.

Because the Regional Water Plan contemplates a transfer of water from the Dell City area to El Paso County around 2030, El Paso Water Utilities (EPWU) has completed this study to better understand the potential groundwater yield of the area. This report is the product of that study and includes a description of previous studies of the area (summarized in Table ES-1), and a discussion of the development, calibration and application of three groundwater flow models of the area.

This study and the resulting models were developed for the internal analyses of EPWU. A draft report and the model files were reviewed by Dr. Robert Mace of the Texas Water Development Board, Dr. G. F. Huff formerly of the United States Geological Survey, and Mr. Steven Finch of John Shomaker and Associates. A meeting of the reviewers was held on June 18, 2008 at the offices of EPWU to discuss comments to the report. The comment letters are provided in Appendix F, as well as responses to those comments.

This report and the model files have been forwarded to the Texas Water Development Board for their future use. As such, this report and the associated models are not official TWDB Groundwater Availability Models (GAMs). However, it is hoped that this effort will assist the TWDB in their development of GAMs for the area.

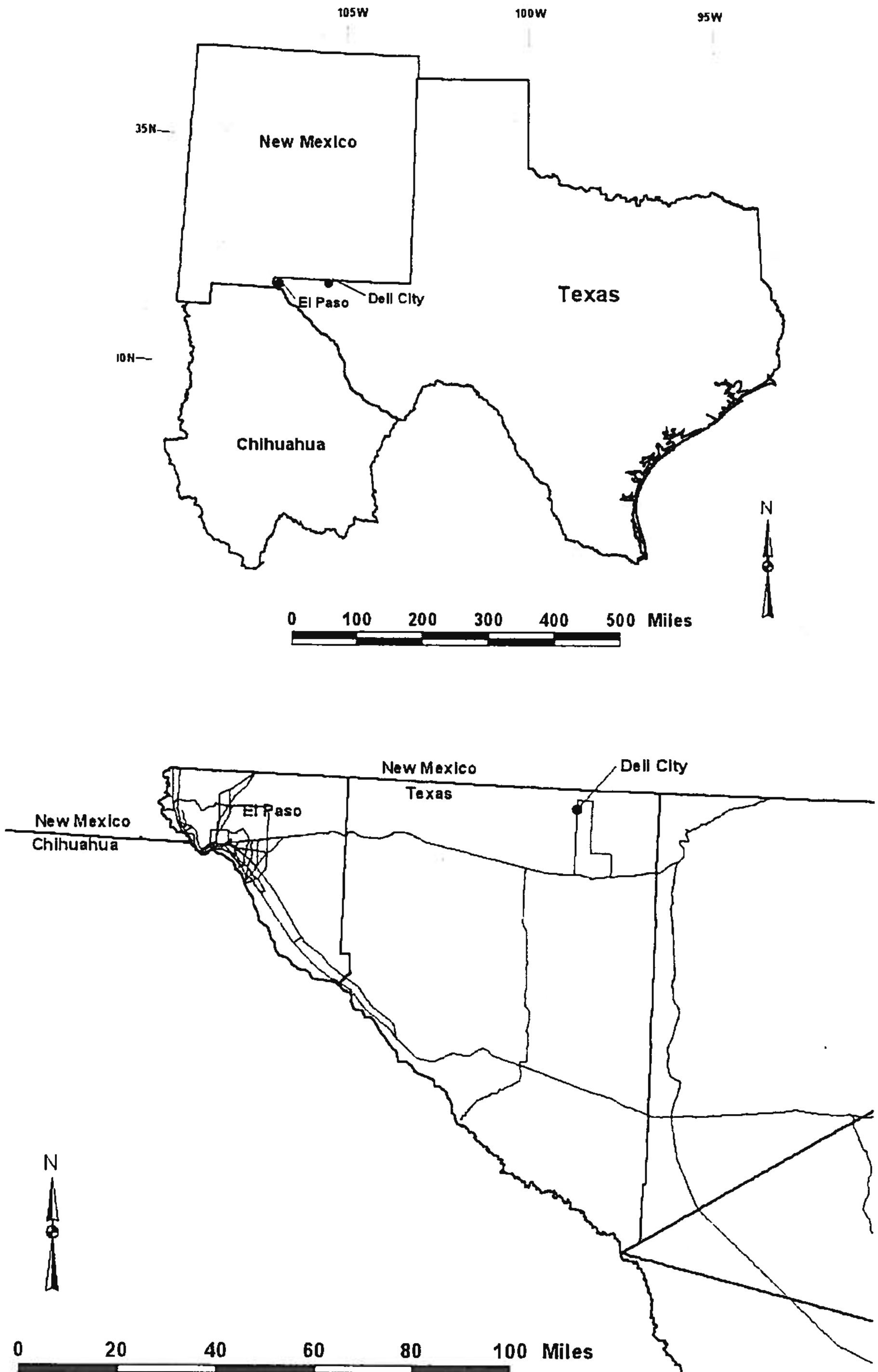


Figure ES-1. Location of Dell City, Texas

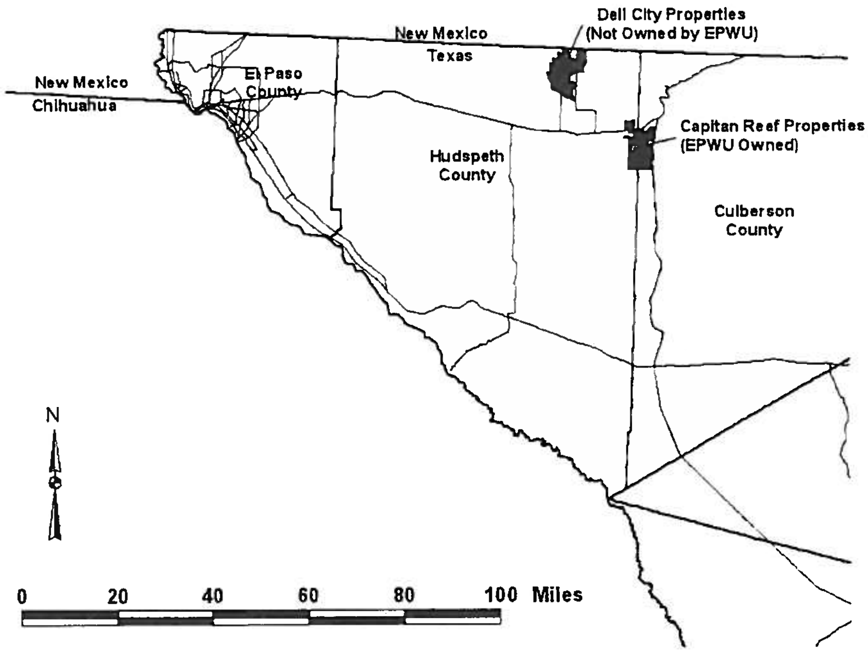


Figure ES-2. Location of Properties in the Dell City Area and Capitan Reef Properties for Potential Future EPWU Groundwater Importation Projects

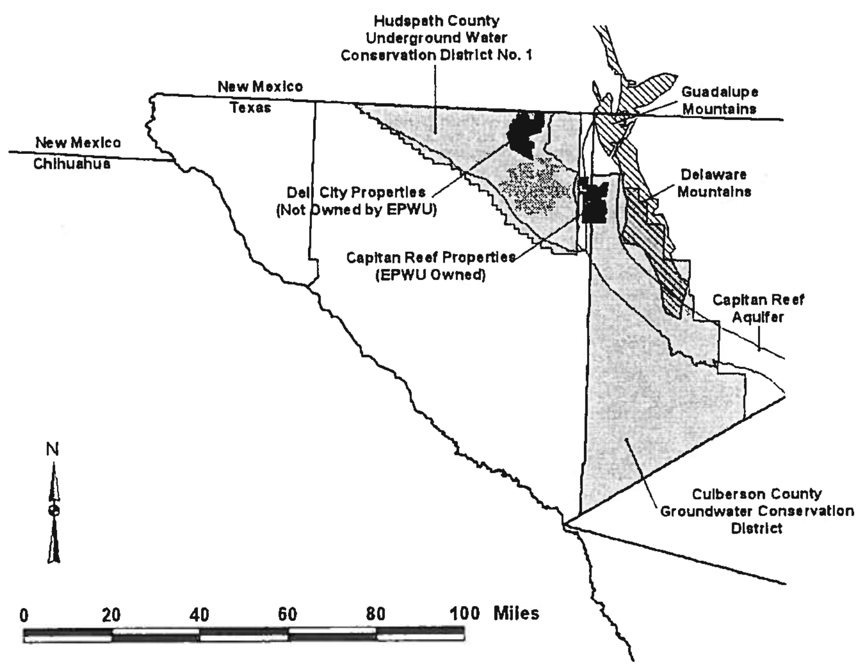


Figure ES-3. Location of Groundwater Conservation Districts in the Dell City Area

Table ES-1. Summary of Previous Studies

Study	Brief Summary of Significant Findings
Scalapino (1950)	First groundwater investigation of area. Recognized recharge to Dell City area was likely from Sacramento River flow.
Bjorklund (1957)	Similar in scope to Scalapino (1950), but focused on Crow Falts area of New Mexico. Estimated recharge to be "probably" less than 100,000 AF/yr.
Reed (1965, 1973, 1980)	Evaluation of groundwater resources of the Diablo Farms area overlying the Capitan Reef aquifer. Estimated inflow to the area of 15,400 AF/yr.
Parizek (1979)	Evaluated potential well locations using fracture trace analysis.
Gates and Others (1980)	Completed geophysical surveys to delineate Goat Seep limestone and Capitan Reef. Also provided updated estimates of pumping and irrigated acreage in the Dell City area.
Kreitler and others (1990)	Groundwater evaluation of the Diablo Plateau area.
Ashworth (1995)	Groundwater investigation of the area underlying irrigable land in Dell City. Estimated recharge to be between 90,000 and 100,000 AF/yr based on evaluation of pumping estimates and groundwater elevation trends.
Mayer (1995)	Developed a steady-state groundwater model to evaluate how regionally pervasive fractures affect regional groundwater flow. Estimated steady-state recharge to be 58,370 AF/yr.
Hibbs and Others (1997)	Compilation of groundwater data for the entire transboundary region of Texas, New Mexico, and Chihuahua, including a map of groundwater elevations in the Dell City area.
Brown and Caldwell (2001)	Groundwater resources investigation of the O'Ban and Layton Farms in Dell City. Provided transmissivity estimates based on aquifer tests.
Blair (2002a, 2002b)	Developed consumptive irrigation requirements for the Dell City area (2002a). Presented data and information regarding alternative estimates of recharge to the area (2002b).
Groeneveld and Baugh (2002)	Completed an analysis of satellite images to develop estimates of evapotranspiration from groundwater-irrigated agriculture and playa discharge in the area. The analysis yielded annual estimates of irrigated acreage and playa discharge.
George and Others (2005)	Summarized and reviewed previous work related to the hydrogeology of Hudspeth County. Recommended an expansion in the boundaries of the Bone Spring-Victorio Peak Aquifer, which was subsequently adopted by the Texas Water Development Board.
Eastoe and Hibbs (2005)	Conducted isotopic sampling of wells in the area. Findings suggested that the isotopic signature of groundwater in Dell City is different than the isotopic signature of groundwater in New Mexico.
Huff and Chace (2006)	Summarized the current state of knowledge in the New Mexico side of the study area.
Livingston Associates and John Shomaker & Associates (2002)	Completed a regional water plan for the New Mexico side of the study area. Estimated "watershed yield" to be 35,078 AF/yr, and estimated that the "sustainable yield" of the groundwater in the area is 150,378 AF/yr (including a groundwater mining component).
Finch (2002)	Completed a groundwater model of the area for the state of New Mexico. Estimated recharge was 54,943 AF/yr.
Finch and Bennett (2002)	Completed an evaluation of groundwater resources in Culberson County, Texas. Estimated groundwater recharge in the Capitan Reef area to be 20,300 AF/yr.

ES 2.0 Conceptual Model of Groundwater Flow

Figure ES-4 depicts the domain of the flow system. The watershed divide between the Otero Mesa and the Tularosa Valley and the Hueco Mountains bound the study area on the west, and the Guadalupe and Delaware Mountains bound the area on the east. The Sacramento Mountains represent the northern boundary, and also represent the source of most of the recharge to the aquifer system. The southern boundary is south of the groundwater divide associated with the Babb Flexure. The flow system is conceptualized to be a single layer or two-dimensional.

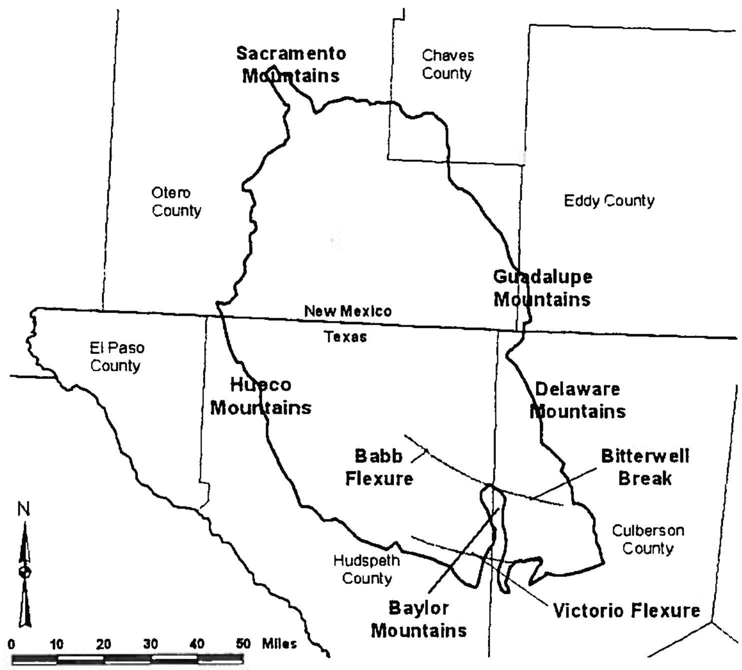


Figure ES-4. Domain of Groundwater Flow System

ES 2.1 Groundwater Occurrence

Groundwater in the study area occurs in three different areas: 1) the upland area associated with the fractured rock aquifers of the Otero Mesa and Diablo Plateau in the western portion of the study, 2) the lower lying area of Quaternary alluvium and playas associated with the Salt Basin and Crow Flats in the central portion of the study area, and 3) the upland area associated with the western slopes of the Guadalupe and Delaware Mountains in the eastern portion of the study area that consist of fractured carbonate rocks of Permian age.

The groundwater in the fractured carbonate rocks is conceptualized to occur in the matrix of the rock, in the fractures of the rock, and in the solutionally widened fractures and bedding plane partings, or conduits. Based on descriptions of the aquifer system described in the literature, previous researchers have considered the aquifer system as being dominated by interconnected conduits. Moreover, the hydrographs of wells in the

Dell City area are well correlated with each other. The aquifer system, therefore, is conceptualized as a system that can be treated as a continuum or equivalent porous media. In this conceptualization, it is assumed that an average hydraulic conductivity or transmissivity can be assigned that is a representation of all three components of permeability.

ES 2.2 Groundwater Movement

In general, groundwater flows from the surrounding highlands towards the playas, the natural discharge point in the study area. Mayer (1995) concluded that groundwater moves preferentially along fracture alignments from the Sacramento Mountains to the Dell City area. Eastoe and Hibbs (2005) found that isotopic signatures of groundwater suggest that there is also a significant portion of recharge in the Texas portion of the Dell City area from the Diablo Plateau, west of Dell City. The numerical model in this investigation tests these assumptions with the use of three conceptual models: one that emphasizes the structural geology findings of Mayer (1995), one that emphasizes the isotopic signature findings of Eastoe and Hibbs (2005), and one that is a hybrid of the structural geology and isotopic signature models.

ES 2.3 Inflow and Outflow

Inflow to the aquifer system is conceptualized to be derived from rainfall that falls within the watershed area. Based on a lack of data to suggest otherwise, it is assumed that there is no flow (even at depth) across the watershed boundaries. In addition, some pumped groundwater is recharged to the aquifer as irrigation return flow. The development of groundwater for irrigation use may have also reversed gradients to the point that groundwater flows into southern end of the study area in the Salt Basin.

Outflow consists of playa evaporation, groundwater pumping, and possibly boundary outflow south of the groundwater divide associated with the Babb Flexure.

ES 3.0 Numerical Model Development

This effort included the development and calibration of three numerical models to further investigate alternative conceptual models of groundwater movement (structural geology, isotope geochemistry, and a hybrid of the structural geology and isotope geochemistry models). All three models were developed with MODFLOW-2000, the industry standard finite-difference code to simulate groundwater flow developed by the US Geological Survey.

The models contain one layer, 281 rows and 171 columns. Cell size is 2,000 ft by 2,000 ft. The time unit for the model is days, and the distance unit for the model is feet, and the bottom of the model domain, specified as 1,000 feet below the land surface elevation. The models define 56 stress periods for the calibration simulation. The first stress period is specified as steady state. This represents the predevelopment period (prior to 1948).

The next 55 stress periods are transient, each with a length of 365 days (1 year). These stress periods represent the years 1948 to 2002.

ES 3.1 Hydraulic Parameters of the Groundwater Flow System

Aquifer transmissivity and storativity were implemented through the assignment of zones that differ in the three models in order to implement the three conceptual models. Hydraulic conductivity and specific storage zones, and the calibrated parameters, for the three models are shown in Figures ES-5 to ES-7. The zones are based on a combination of geology and elevation. The calibrated estimates of hydraulic conductivity and specific storage for each of the models are shown on each zonation figure. Transmissivity and storativity estimates are also provided based on the model assumptions of 1,000 ft aquifer thickness.

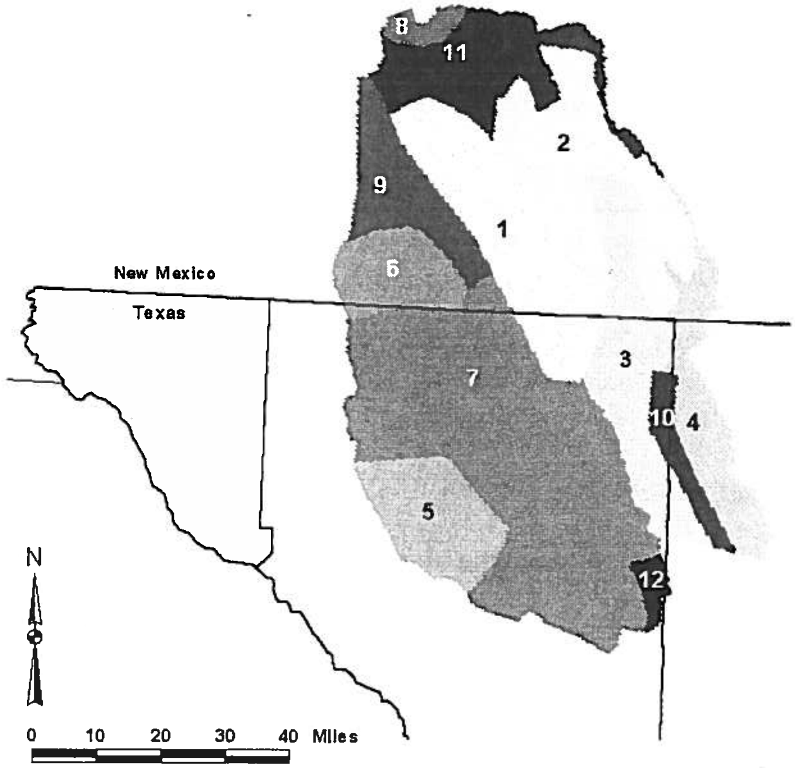
ES 3.2 Groundwater Pumping

Estimates of net groundwater pumping were based on irrigated acreage estimates and crop duties. Net pumping is total pumping less the water that infiltrates past the root zone (leaching fraction). Since the model stress periods are annual, and groundwater hydrographs suggest that excess irrigation water percolates back to the water table in the same years as irrigation occurs, it is not possible to estimate total pumping with this modeling approach.

Irrigated acreage estimates were divided into 24 zones to facilitate development (Figure ES-8). Values were adjusted during model calibration. Average estimates of pumping for all models for selected time period are presented in Table ES-2.

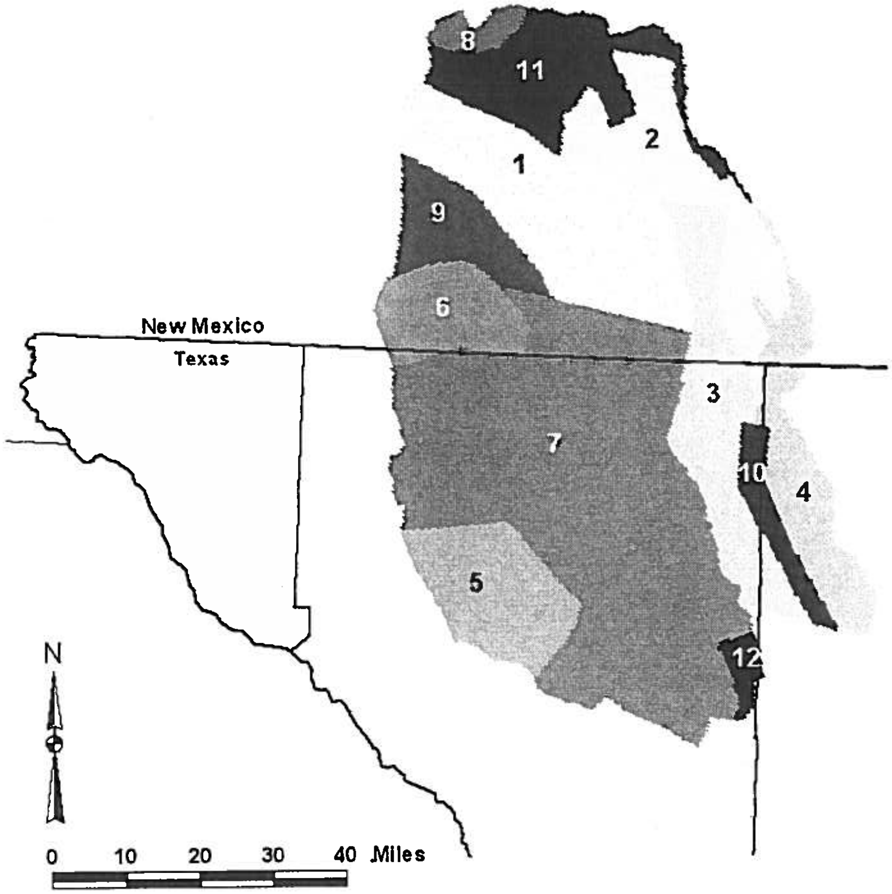
Table ES-2. Average Net Pumping Estimates for Entire Model Domain for Selected Time Periods

Period	Average Pumping (AF/yr)
1948-1950	45,162
1951-1960	74,691
1961-1970	89,899
1971-1980	116,116
1981-1990	77,061
1991-2000	88,706
2001-2002	115,723
1948-2002	87,849



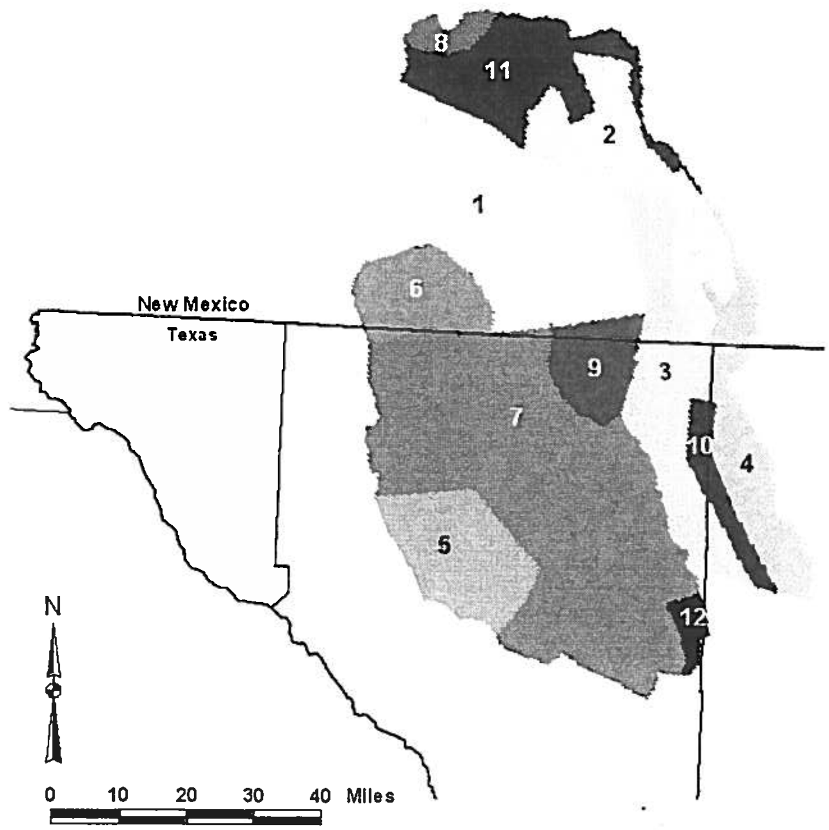
Zone	Area (mi^2)	Hydraulic Conductivity (ft/day)		Specific Storage (day^{-1})	Transmissivity (ft^2/day)		Storativity (dimensionless)
		x-direction	y-direction		x-direction	y-direction	
1	540	98.4	179	1.14E-04	98,445	178,545	1.14E-01
2	597	2.01	0.48	1.86E-06	2,007	485	1.86E-03
3	424	49.7	176	2.00E-04	49,745	176,292	2.00E-01
4	309	14.3	5.31	3.56E-07	14,340	5,308	3.56E-04
5	316	0.11	0.45	7.96E-06	113	449	7.96E-03
6	225	2.39E-03	4.17E-03	1.81E-05	2.39	4.17	1.81E-02
7	1,505	10.7	1.00	5.23E-05	10,737	1,000	5.23E-02
8	55	100	146	1.57E-04	100,000	145,932	1.57E-01
9	273	1.00E-03	1.00E-03	3.26E-07	1.00	1.00	3.26E-04
10	96	19.8	40.0	2.70E-06	19,787	39,966	2.70E-03
11	392	4.95	1.01	1.00E-07	4,945	1,015	1.00E-04
12	41	5.48	0.02	1.06E-05	5,479	19.1	1.06E-02

Figure ES-5. Aquifer Hydraulic Conductivity and Storativity Zonation – Structural Geology Model



Zone	Area (mi^2)	Hydraulic Conductivity (ft/day)		Specific Storage (day^{-1})	Transmissivity (ft^2/day)		Storativity (dimensionless)
		x-direction	y-direction		x-direction	y-direction	
1	598	1.00	98.2	1.00E-07	1,000	98,153	1.00E-04
2	424	1.31	0.43	4.50E-06	1,312	428	4.50E-03
3	419	31.0	17.7	2.00E-04	30,963	17,683	2.00E-01
4	309	100	8.86	2.00E-04	100,000	8,862	2.00E-01
5	316	0.11	1.69	7.28E-06	108	1,690	7.28E-03
6	225	2.42E-03	3.80E-03	2.00E-04	2.42	3.80	2.00E-01
7	1,726	50.0	87.6	2.00E-04	50,000	87,590	2.00E-01
8	55	100	200	2.00E-04	100,000	200,000	2.00E-01
9	198	0.04	2.66	1.00E-07	38.4	2,661	1.00E-04
10	96	6.60	1.00	3.84E-07	6,603	1,000	3.84E-04
11	365	2.16	0.44	1.00E-07	2,162	440	1.00E-04
12	41	0.03	9.86	5.37E-06	26.9	9,860	5.37E-03

Figure ES-6. Aquifer Hydraulic Conductivity and Storativity Zonation – Isotope Geochemistry Model



Zone	Area (mi²)	Hydraulic Conductivity (ft/day)		Specific Storage (day⁻¹)	Transmissivity (ft²/day)		Storativity (dimensionless)
		x-direction	y-direction		x-direction	y-direction	
1	903	1.00	46.7	1.00E-07	1,000	46,682	1.00E-04
2	424	1.09	0.48	4.13E-06	1,089	479	4.13E-03
3	419	8.67	75.3	2.00E-04	8,675	75,275	2.00E-01
4	309	24.2	4.63	2.40E-07	24,174	4,630	2.40E-04
5	316	0.11	1.66	7.25E-06	109	1,663	7.25E-03
6	220	3.02E-03	5.10E-03	6.36E-05	3.02	5.10	6.36E-02
7	1,456	50.00	1.00	2.00E-04	50,000	1,000	2.00E-01
8	55	100.00	200.00	2.00E-04	100,000	200,000	2.00E-01
9	167	200.00	193.23	2.00E-04	200,000	193,231	2.00E-01
10	96	1.81	34.8	2.00E-04	1,807	34,817	2.00E-01
11	365	2.53	0.38	1.00E-07	2,526	380	1.00E-04
12	41	1.15	0.02	3.66E-06	1,153	24.8	3.66E-03

Figure ES-7. Aquifer Hydraulic Conductivity and Storativity Zonation – Hybrid Model

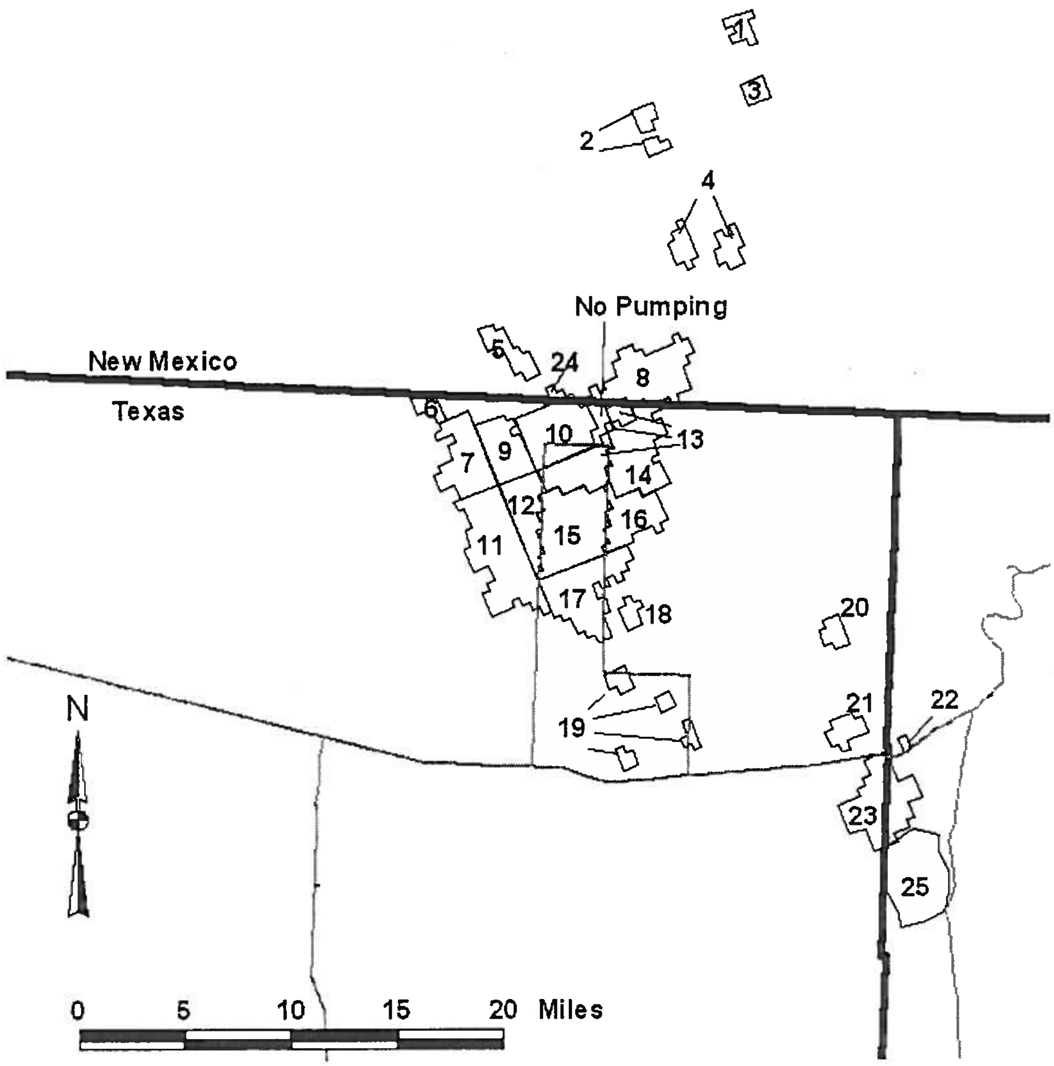


Figure ES-8. Irrigation Pumping Zones

ES 3.3 Recharge

Annual estimates of recharge to the groundwater flow system were developed based on annual precipitation. Precipitation in the area is higher in areas of higher elevations and lower in areas of lower elevations based on an analysis of precipitation data in the region. Average precipitation of each cell in the model was estimated based on land surface elevation. Annual variations in precipitation for the calibration period (1948 to 2002) were based on historic records, including a dampening factor to slightly raise dry years and slightly decrease wet years. This is intended to simulate the lag time associated with travel time through the unsaturated zone. The dampened annual recharge factors data are summarized in Figure ES-9.

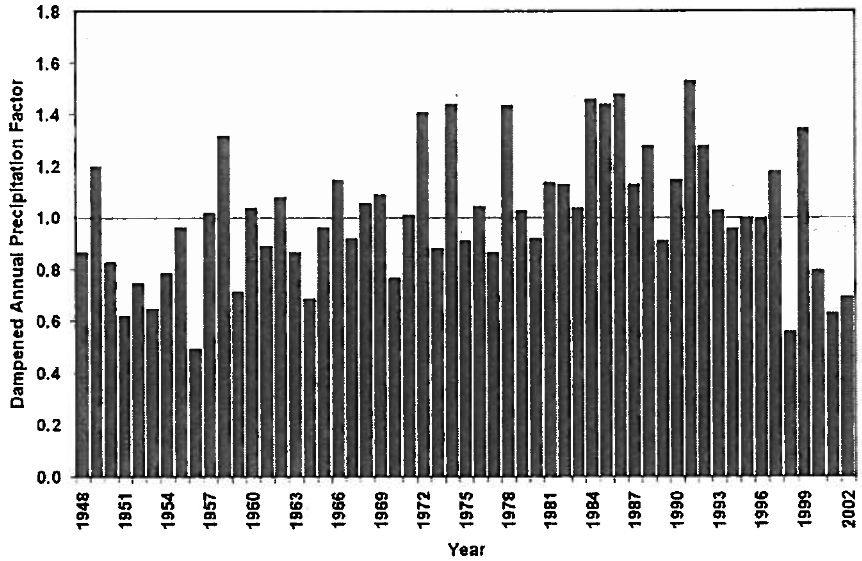


Figure ES-9. Annual Precipitation Factors with a Dampening Factor of 0.1

Recharge estimates were based on a modified Maxey-Eakin approach (i.e. higher elevation areas have a higher recharge rate than lower elevation areas and higher precipitation years have a higher recharge rate than low precipitation years). Generally, areas above elevation 5,400 ft receive higher recharge than areas below 5,400 ft elevation. Based on model calibration, the following rates are applied to those areas that are above the "Maxey Eakin" elevation:

- If the annual precipitation is equal to or less than 7 in/yr, the recharge rate is set to 0% of precipitation.
- If the annual precipitation is between 7 and 15 in/yr, the recharge rate is set to 1% of precipitation.
- If the annul precipitation is between 15 and 25 in/yr, the recharge rate is set to 10% of precipitation.
- If the annual precipitation is greater than or equal to 25 in/yr, the recharge rate is set to 25% of precipitation. Below the Maxey-Eakin elevation, a standard recharge rate of is applied (assumed to be 0.005 in/yr).

Recharge estimates for selected time periods for the entire model domain (averaged for all three models) are summarized in Table ES-3.

Table ES-3. Average Recharge Estimates for the Entire Model Domain

Period	Average Recharge (AF/yr)
Steady-State (pre-1948)	62,916
1948-50	53,669
1951-60	38,186
1961-70	51,283
1971-80	87,492
1981-90	114,150
1991-2000	84,692
2001-02	7,598
1948-2002	71,531

ES 3.4 Other Model Input Parameters/Boundary Conditions

Other model input parameters were handled by a variety of MODFLOW-2000 packages such as drain, evapotranspiration, general head boundaries, horizontal flow barrier, and constant head boundary. The solver package used was the geometric multigrid (GMG) solver.

ES 4.0 Model Calibration Results

Calibration of the three groundwater flow models was accomplished by adjusting various parameters until model estimated groundwater elevations were in reasonable agreement with actual groundwater elevations. The calibration period was 1948 to 2002 (55 annual stress periods), with a steady-state stress period preceding the transient calibration (i.e. stress period 1) for a total of 56 stress periods.

The locations of the 369 wells that were used in the calibration are shown in Figure ES-10. These wells had at least groundwater elevation measurement from 1948 to 2002. The total number of groundwater elevation measurements from these 369 wells used in the calibration was 2,438.

ES 4.1 Groundwater Elevation Comparison

The three models were calibrated individually using a combination of trial-and-error parameter adjustments and automated adjustments using PEST, an industry-standard inverse modeling software package. Calibration of the models was partly evaluated through a series of comparisons between model estimated groundwater elevations and measured groundwater elevations. Graphical summaries of the match between measured groundwater elevations and model estimated groundwater elevations are presented in Figures ES-11 to ES-13.

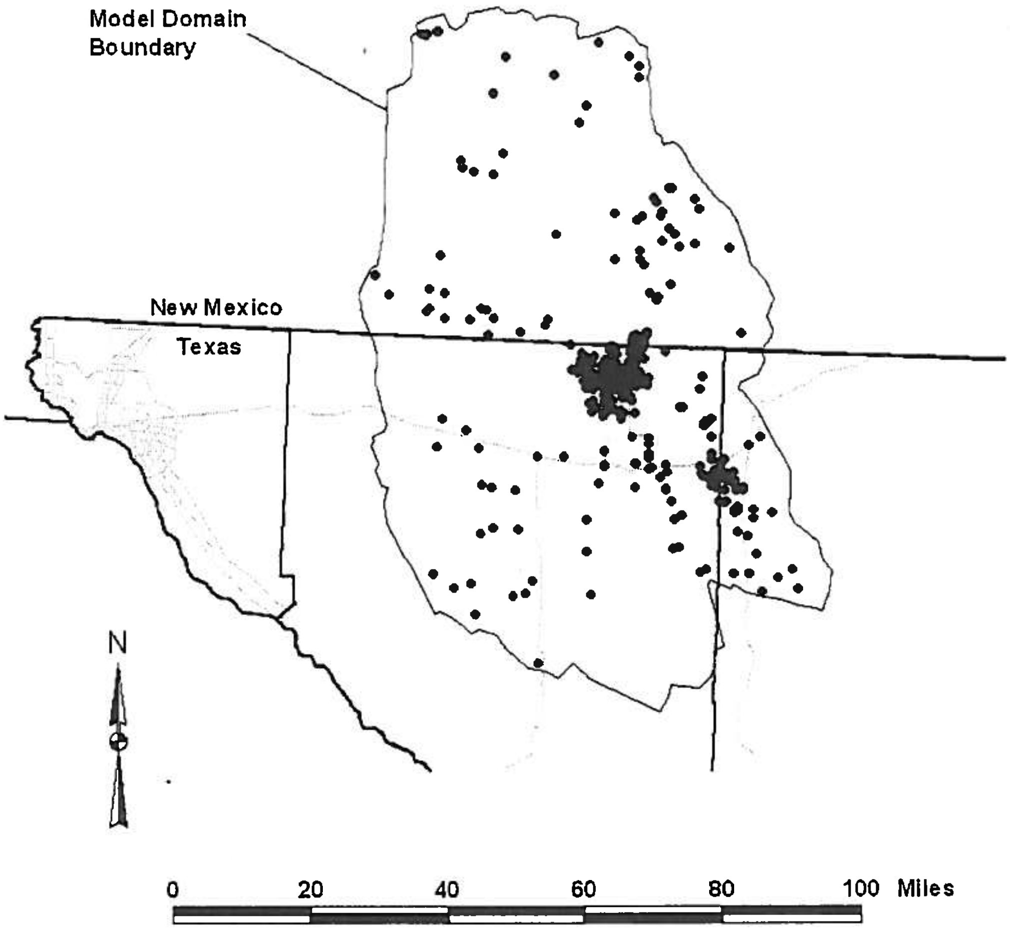


Figure ES-10. Location of Wells with Groundwater Elevation Measurements used in Model Calibration.

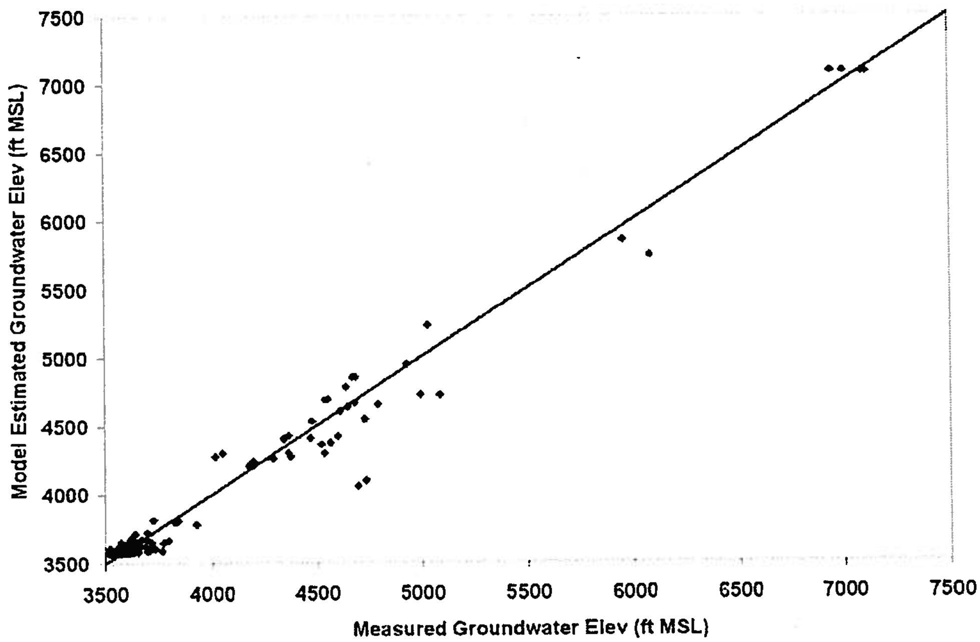


Figure ES-11. Measured Groundwater Elevations vs. Model Estimated Groundwater Elevations
Structural Geology Model

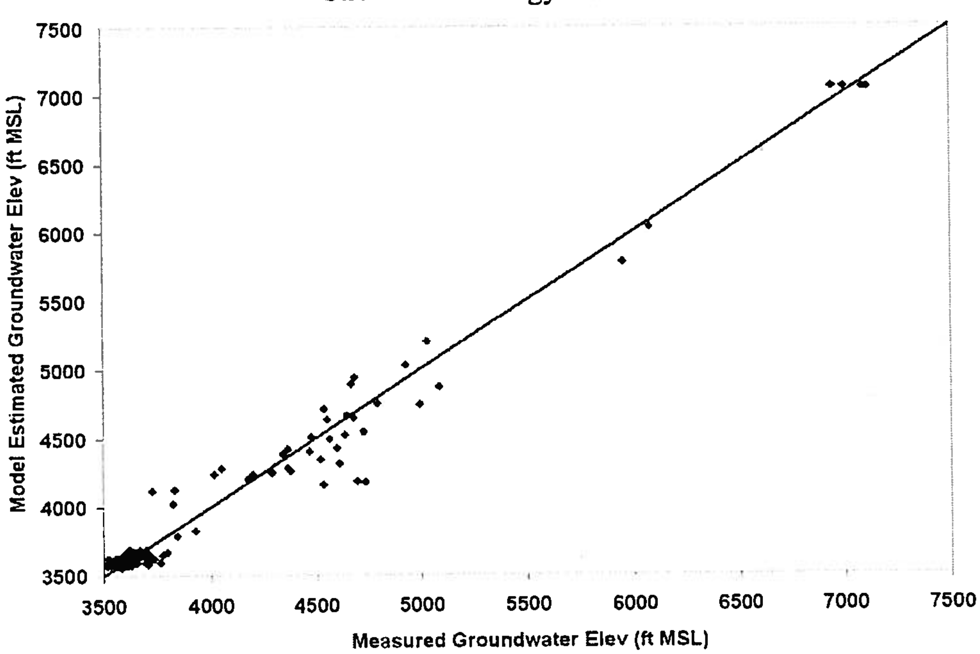


Figure ES-12. Measured Groundwater Elevations vs. Model Estimated Groundwater Elevations
Isotope Geochemistry Model

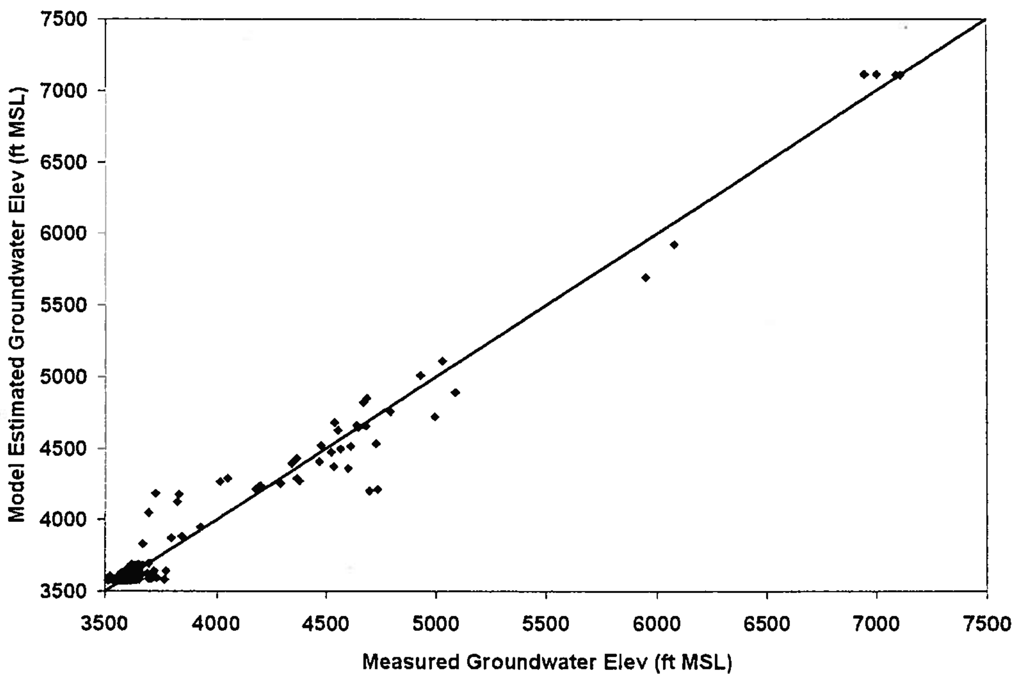


Figure ES-13. Measured Groundwater Elevations vs. Model Estimated Groundwater Elevations
Hybrid Model

ES 4.2 Irrigated Acreage Estimates

Model calibration included adjustments to initial annual estimates of groundwater pumping. The resulting pumping estimates were used in conjunction with the initial annual estimates of irrigated acreage. Based on this analysis, it appears that consumptive pumping prior to 1993 was on the order 3 AF/ac. Flood irrigation typically results in high total pumping and significant infiltration of return water. Because the model relies on estimates of consumptive or net pumping and includes an underlying assumption that irrigation water infiltrates back to the water table within the year in which it was pumped, this modeling analysis can provide no insight into estimates of total pumping, or, by extension, the amount of water that infiltrates back to the aquifer (i.e. the leaching fraction).

After 1993 and the introduction of center pivots in the area, it appears that the consumptive or net pumping is about 5 AF/ac. It is possible that total pumping on a per acre basis has decreased since the period of flood irrigation, but this modeling analysis cannot be used to evaluate this commonly held assumption. It is clear, however, that there is a distinct difference in the consumptive duties before and after the introduction of center pivots as the dominant irrigation method in the area.

Based on this conclusion, Figure ES-14 presents an interpreted estimate of irrigated acreage in the area. Irrigated acreage rose from less than 10,000 acres in 1948 to about

25,000 acres in the mid 1950s. From the mid 1950s to the mid 1980s, irrigated acreage fluctuated between about 20,000 acres to as high as about 45,000 acres. From the early 1980s to 2002, irrigated acreage has been relatively constant at slightly over 20,000 acres, except for declines in 1993 and 1994.

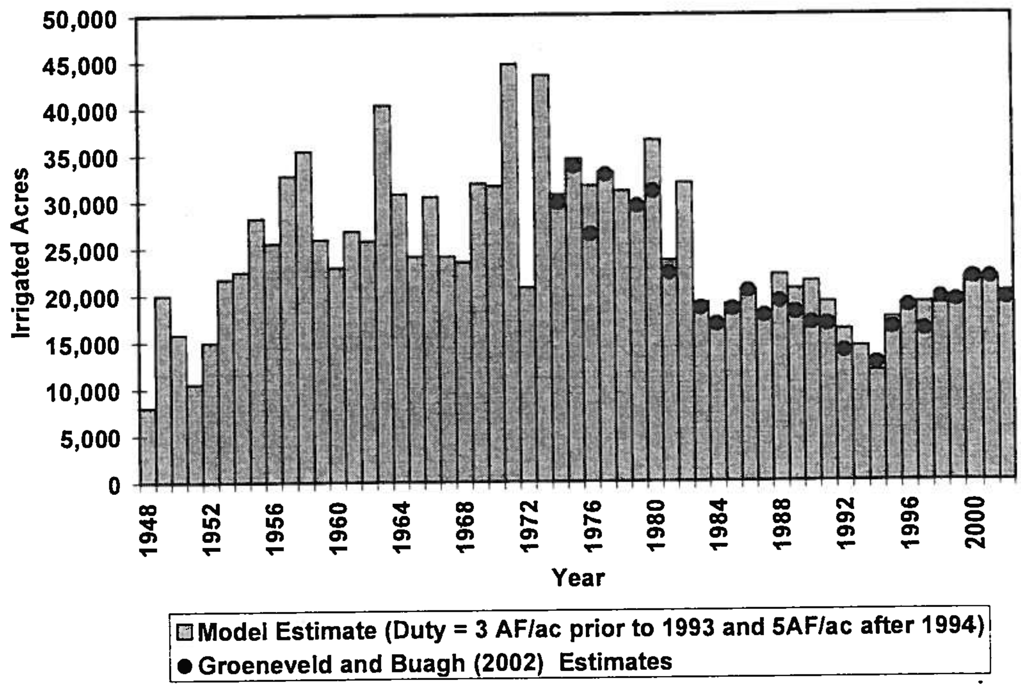


Figure ES-14. Summary Estimate of Irrigated Acreage

ES 4.3 Water Budget Analysis

The groundwater budgets for the three models for the entire model domain are summarized in Table ES-4. This summary presents groundwater budgets for the steady state period (pre-1948 or stress period 1) and the average of the transient calibration period (1948 to 2002). Note that all values have been rounded to the nearest 1,000 AF/yr.

Details of the annual changes to the key components of the water budget and discussed more thoroughly in the report, as well as more detailed subregional groundwater budgets of the original Bone Spring-Victorio Peak Aquifer, the new Bone Spring-Victorio Peak Aquifer, the original Hudspeth County Underground Water Conservation District No.1, the new Hudspeth County Underground Water Conservation District No.1 (HCUWCD), and the EPWU Capitan Reef properties. Because of its significance in the management of groundwater in the area, the zonation used for the subregional groundwater budget for the new boundaries of the HCUWCD is presented as Figure ES-15, and the subregional groundwater budget is presented as Table ES-5.

Table ES-4. Summary Groundwater Budgets for the Entire Model Domain
All Values in AF/yr and rounded to nearest 1,000 AF/yr

	Structural Geology		Isotope Geochemistry		Hybrid	
	Pre-1948 (Steady State)	1948-2002 Average	Pre-1948 (Steady State)	1948-2002 Average	Pre-1948 (Steady State)	1948-2002 Average
Northern Boundary	41,000	40,000	19,000	19,000	16,000	17,000
Southern Boundary	< 1,000	< 1,000	0	0	0	0
Recharge	63,000	74,000	63,000	70,000	63,000	70,000
Total Inflow	104,000	114,000	82,000	89,000	79,000	87,000
Northwestern Boundary	< 1,000	< 1,000	< 1,000	< 1,000	< 1,000	< 1,000
Southern Boundary	< 1,000	< 1,000	3,000	4,000	< 1,000	2,000
Evapotranspiration	104,000	67,000	79,000	52,000	79,000	49,000
Total Natural Outflow	104,000	67,000	82,000	56,000	79,000	51,000
Groundwater Pumping	0	88,000	0	88,000	0	88,000
Groundwater Storage Decline	0	41,000	0	55,000	0	52,000

Table ES-5. Subregional Groundwater Budget for the New Hudspeth County
Underground Water Conservation District No.1 (HCUWCD)
All Values in AF/yr

	Structural Geology		Isotope Geochemistry		Hybrid	
	Pre-1948 (Steady State)	1948-2002 Average	Pre-1948 (Steady State)	1948-2002 Average	Pre-1948 (Steady State)	1948-2002 Average
Inflow from New Mexico	76,000	95,000	54,000	65,000	53,000	56,000
Inflow from Hudspeth County Southwest of HCUWCD	3,000	5,000	4,000	13,000	3,000	10,000
Inflow from Hudspeth County East of HCUWCD	9,000	10,000	3,000	4,000	9,000	9,000
Recharge	<1,000	<1,000	<1,000	<1,000	<1,000	<1,000
Total Inflow	88,000	110,000	61,000	82,000	65,000	75,000
Evapotranspiration	88,000	51,000	61,000	36,000	65,000	34,000
Total Natural Outflow	88,000	51,000	61,000	36,000	65,000	34,000
Groundwater Pumping	0	80,000	0	80,000	0	80,000
Groundwater Storage Decline	0	21,000	0	34,000	0	39,000

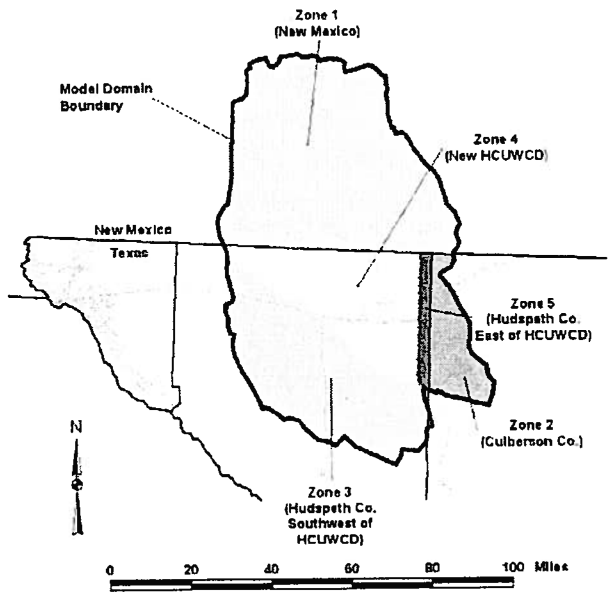


Figure ES-15. Subregional Zones used for Analysis of the New Hudspeth County Underground Water Conservation District No.1 (HCUWCD)

ES 5.0 Simulation of Potential Future Conditions

The models were used to simulate potential future conditions by examining two key variables: alternative climatic conditions and alternative pumping scenarios. The objective of the simulations was to develop an understanding of groundwater yields within the new boundaries of the Hudspeth County Underground Water Conservation District No. 1 (HCUWCD). The alternative climatic conditions were based on a series of 50-year simulations that were derived from a tree-ring data set for New Mexico (and Arizona) that covers the years 1000 to 1988. The alternative pumping scenarios were based on the HCUWCD rules and variations on those rules for the purposes of understanding the sensitivity of relaxation or tightening of the regulations. These simulations were run to develop information related to groundwater elevation changes under various pumping scenarios, not to suggest or recommend changes to those rules.

The three models, 16 pumping scenarios (including the scenario with zero pumping) and 7 climatic scenarios were used to develop 336 simulations. Because the calibrated models used a decreasing boundary head for the southern boundary, and because it is unknown whether the same rate of decline would continue into the future, two sets of assumptions were applied to the future simulations: one set of 336 simulations were run assuming the same rate of decline, and one set of 336 simulations where the 2002 boundary heads are held constant. Therefore, a total of 772 simulations were run. Each simulation was run for 50 years, and the heads at the end of 2002 were used to initiate the solution.

The results of the simulation demonstrated that the two alternative southern boundary heads made no significant difference to groundwater elevation changes or groundwater budget components in the Dell City area. Therefore, only the results from the decreasing southern boundary are presented.

Figure ES-16 presents groundwater pumping vs. groundwater storage change within the new boundaries of the HCUWCD. At zero pumping, the groundwater storage increase ranges from about 12,000 AF/yr to about 35,000 AF/yr. The range is attributable to alternative climatic (or recharge) scenarios. At the other extreme, pumping over 120,000 AF/yr would result in a storage decline of between about 10,000 AF/yr to about 50,000 AF/yr, depending on climatic conditions. For pumping scenarios above about 54,000 AF/yr, groundwater storage would decline; pumping less than about 54,000 AF/yr would generally result in groundwater storage increases.

The observed vertical spreads for individual models is due to varying climatic, or recharge conditions. The ranges are consistent with observed conditions from 1948 to 2002. Recall that groundwater elevations dropped after the start of irrigation pumping in 1948. Since the 1980s, groundwater elevations have essentially stabilized due to the combined effect of decreased pumping and increased recharge.

Note that the structural geology model exhibits less groundwater storage decline due to pumping than the other two models. This is apparently due to the higher induced inflow from New Mexico and reduced evapotranspiration. These "captured" flows result in less drawdown than the other models.

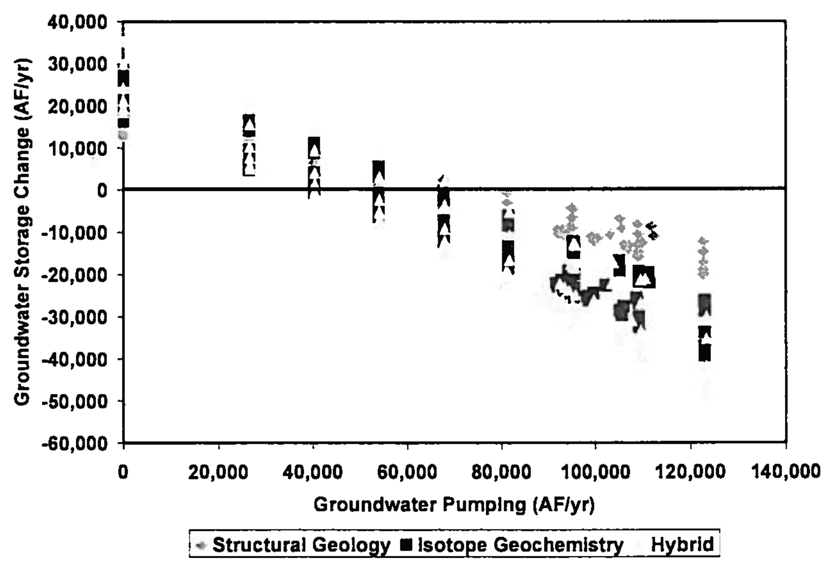


Figure ES-16. Simulation Results for the New HCUWCD Zone
Groundwater Pumping vs. Groundwater Storage Change within HCUWCD

Based on the summaries of groundwater pumping vs. groundwater storage change within the new boundaries of the HCUWCD, zero storage change would be achieved with net pumping between 40,000 AF/yr and 68,000 AF/yr. Table ES-6 summarizes the results.

Table ES-6. Summary of Net Groundwater Pumping that Would Result in Zero Storage Change (50-Year Average)

Scenario Number	Climatic Scenario Description	Precipitation (% of Average)	Pumping (AF/yr)
C1	Driest	87	40,000
C2	Wettest	131	68,000
C3	Lowest Standard Deviation	94	40,000
C4	Highest Standard Deviation	111	68,000
C5	Average - Low Standard Deviation	100	40,000
C6	Average - Intermediate Standard Deviation	100	40,000
C7	Average - High Standard Deviation	100	54,000

If "sustainability" means maintaining a zero groundwater storage change, HCUWCD would need to reduce pumping from what has historically occurred, and from what is currently permitted under the HCUWCD rules based on the results of this investigation. However, in order to put the issue of zero storage change into some perspective, the analysis was advanced to consider the relationship between groundwater storage change over the entire district, and groundwater elevation changes, both over the entire district and within the irrigated area of HCUWCD (Figure ES-17).

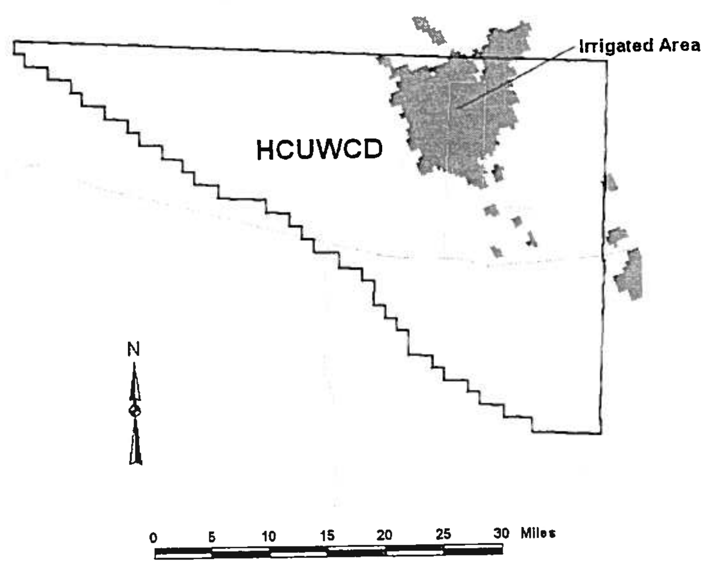


Figure ES-17. Irrigated Area of HCUWCD

The relationship between groundwater storage change within HCUWCD and average drawdown after 50 years for all simulations is presented in Figures ES-18 and ES-19. Figure ES-19 plots groundwater storage change in HCUWCD and Average Drawdown for all of HCUWCD for all simulations, with each model shown separately.

Note that for zero storage change, drawdown is also zero for all three models. For equal storage declines, the structural geology model suggests that the drawdown will be greater than for the other two models. This is due to different specific storages and, hence, different storativities between the models. The structural geology model assumes that the specific storage in the HCUWCD area is 1.1E-04 ft^{-1}. The isotope geochemistry model and the hybrid model assume a value of 2.0E-04 ft^{-1}. Assuming an aquifer thickness of 1,000 ft, this translates to storativity values of 0.11 and 0.2, respectively. Since the isotope geochemistry model and the hybrid model have a storativity value nearly twice that of the structural geology model, the relationship in Figure ES-18 between the three models is expected, and highlights the sensitivity of that parameter.

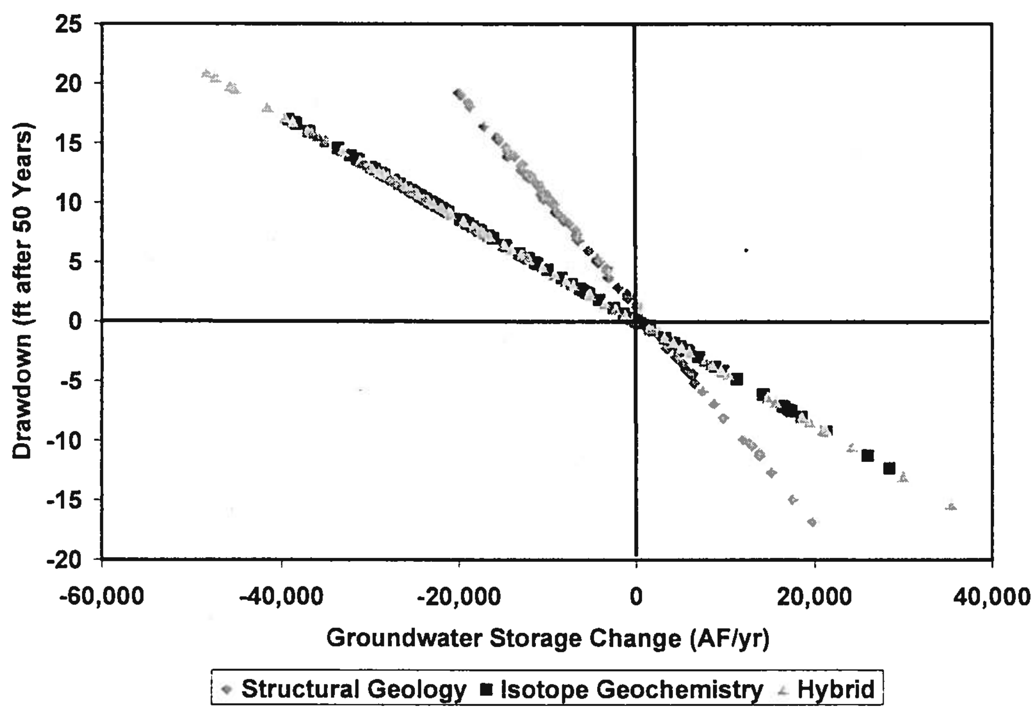


Figure ES-18. Groundwater Storage Change in HCUWCD vs.
Average Drawdown after 50 Years in HCUWCD

In order to understand what the groundwater storage change rate throughout HCUWCD means in terms of drawdown within the irrigated area, Figure ES-19 plots groundwater storage change in HCUWCD vs. the drawdown in the irrigated area of HCUWCD. Note that at zero storage change, a rise in groundwater elevations of between 9 and 17 feet is estimated depending on the model and the climatic scenario after 50 years in the irrigated area. Zero drawdown in the irrigated area occurs when the groundwater storage decline in the entire HCUWCD is between about 3,000 AF/yr and about 14,000 AF/yr. Based on the estimated relationship between pumping and groundwater storage change, pumping at 67,000 AF/yr would always result in a storage decline of less than 14,000 AF/yr. Pumping between 67,000 and 95,000 AF/yr would result in less than 14,000 AF/yr of groundwater storage decline in wet, average, and slightly below average precipitation periods.

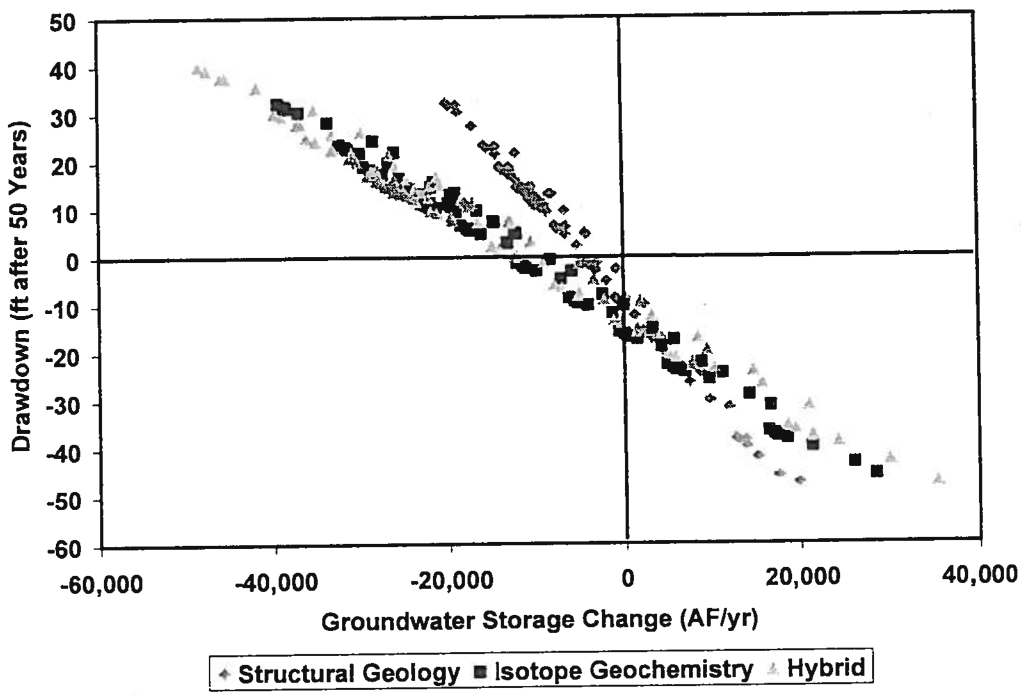


Figure ES-19. Groundwater Storage Change in HCUWCD vs. Average Drawdown after 50 Years in Irrigated Area of HCUWCD

ES 6.0 Summary and Conclusions

The Dell City area may become a source of municipal water supply for El Paso. In order to better understand the area and develop estimates of groundwater yields from the area, this study was completed by El Paso Water Utilities for internal analysis. The study included a review of previous work, the development of three numerical groundwater flow models to test various aspects of the conceptual model of groundwater flow in the area, and the application of the three groundwater flow models under various climatic and pumping scenarios to estimate groundwater yields in the area. This report and the model files have been forwarded to the Texas Water Development Board for their future use. As such, this report and the associated models are not official TWDB Groundwater Availability Models (GAMs). However, it is hoped that this effort will assist the TWDB in their development of GAMs for the area.

Significant conclusions of this study are:

- Total inflow (recharge plus boundary flows) estimates for the entire model domain under predevelopment conditions ranged between 79,000 and 104,000 AF/yr, depending on the model used
- Average total inflow (recharge plus boundary flows) estimates from 1948 to 2002 ranged between 87,000 and 114,000 AF/yr, depending on the model used. Note that total inflow increased as a result of a combination of pumping and high recharge in latter years of the simulation period.
- The recharge estimates are generally consistent with and slightly higher than previous estimates as documented in the literature.
- Evapotranspiration from the playa area east of Dell City prior to 1948 ranged from 79,000 to 104,000, depending on the model used to make the estimate.
- Average evapotranspiration from the playa from 1948 to 2002 ranged from 49,000 to 67,000 AF/yr.
- Average total consumptive pumping in the area from 1948 to 2002 was about 88,000 AF/yr
- Irrigated acreage in the area rose from less than 10,000 acres in 1948 to about 25,000 acres in the mid 1950s. From the mid 1950s to the mid 1980s, irrigated acreage fluctuated between about 20,000 acres to as high as 45,000 acres. From the early 1980s to 2002, irrigated acreage was relatively constant at slightly over 20,000 acres, except for declines in 1993 and 1994.
- Prior to 1993 and the widespread use of center pivot irrigation, consumptive duty on irrigated lands was about 3 AF/ac. After 1993, consumptive duty on irrigated lands was about 5 AF/ac. Due to the nature of the modeling approach used, it is not possible to make any estimates or draw any conclusions regarding total pumping (consumptive pumping plus leaching fraction), or estimate the leaching fraction.
- Historic groundwater pumping from 1948 to 2002 in the new boundary of HCUWCD averaged about 80,000 AF/yr. This pumping resulted in:
    - Between 3,000 and 19,000 AF/yr of increased inflow from New Mexico (depending on the model used).
    - Between 2,000 and 9,000 AF/yr of increased inflow from the Diablo Plateau, southwest of HCUWCD (depending on the model used).
    - Between 0 and 1,000 AF/yr of increased inflow from the area in Hudspeth County east of HCUWCD (depending on the model used).
    - Between 25,000 and 37,000 AF/yr of decreased evapotranspiration for the playa area within HCUWCD (depending on the model used).

- Between 21,000 and 39,000 AF/yr of decreased groundwater storage within HCUWCD (depending on the model used).

- Groundwater yield in the Dell City area ranges from 54,000 to 95.000 AF/yr (net or consumptive pumping), depending on climatic condition, and depending on the definition of "sustainability" that could be applied by the board of HCUWCD.

1.0 INTRODUCTION

The area surrounding Dell City in Hudspeth County, Texas (Figure 1) has been an important agricultural area since the late 1940s. Irrigation water is pumped from a fractured rock aquifer that extends north into New Mexico. Wells in the area can produce 3,000 gallons per minute (gpm) or more.

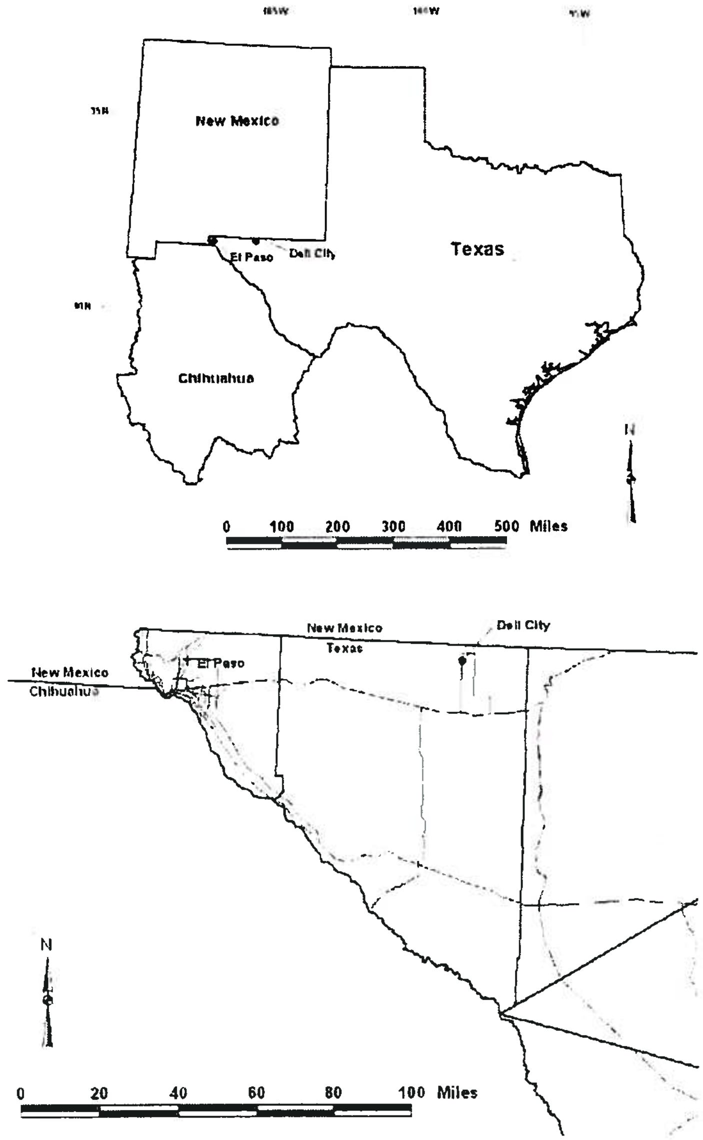


Figure 1. Location of Dell City, Texas

The Texas Water Development Board (TWDB) has designated portions of the area as "minor" aquifers (the Bone Spring-Victorio Peak Aquifer and the Capitan Reef Aquifer, Figure 2). The original designation of the Bone Spring-Victorio Peak Aquifer was based on the extent of the aquifer system in Texas that underlies irrigable land (Ashworth, 1995, pg. 1). Recently, based on the findings of George and others (2005), TWDB has extended the boundaries of the Bone Spring-Victorio Peak Aquifer to include areas to the south and west of the old designation.

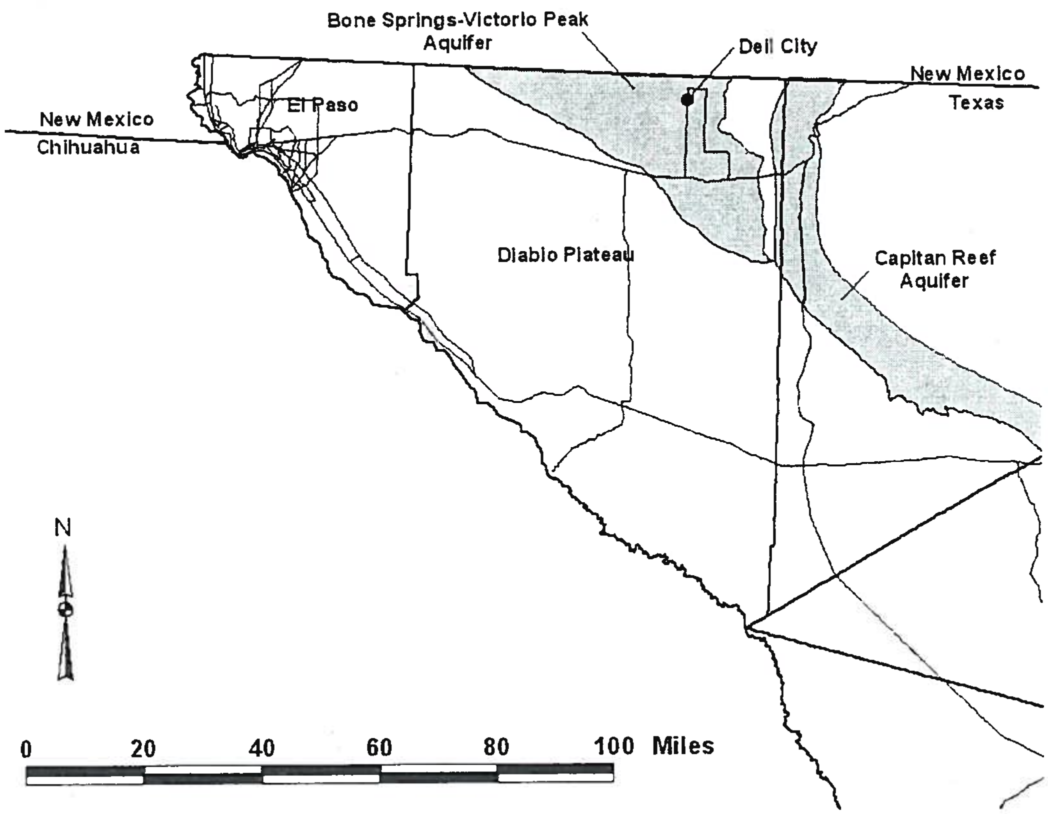


Figure 2. Location of Bone Spring-Victorio Peak Aquifer and Capitan Reef Aquifer as Currently Designated by the Texas Water Development Board

A large portion of the study area known as the Diablo Plateau lies generally south and west of the Bone Spring-Victorio Peak Aquifer (also shown in Figure 2). The aquifer system that underlies the Diablo Plateau consists primarily of the same limestone formations that compose the Bone Spring-Victorio Peak Aquifer. Mullican and Mace (2001, pg. 257) noted that as hydrogeologic evaluations of this area advance, the Diablo Plateau may warrant future designation as a "minor" aquifer by TWDB.

In recent years, the area has been considered to be a potential source of water supply for El Paso, located about 75 miles west of Dell City. The 2006 Regional Water Plan (FWTRPG, 2006 and Gooch and others, 2006) has identified properties currently owned by EPWU overlying the Capitan Reef Aquifer, and Dell City properties overlying the Bone Spring-Victorio Peak Aquifer that are not owned by EPWU for groundwater transfer beginning around 2030. These properties are shown in Figure 3.

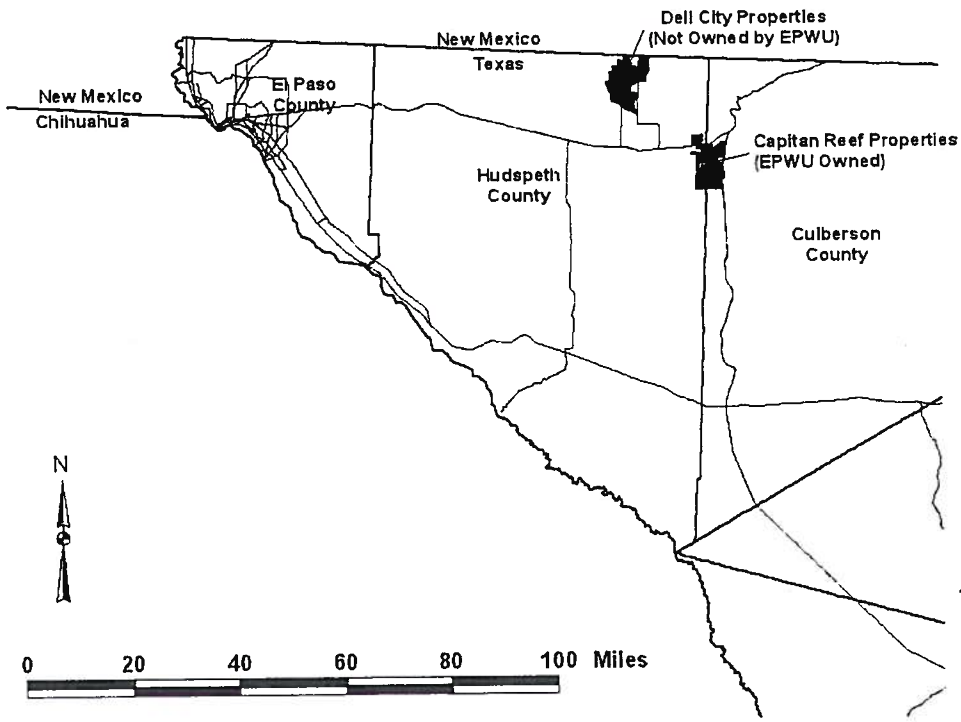


Figure 3. Location of Properties in the Dell City Area and Capitan Reef Properties for Potential Future EPWU Groundwater Importation Projects

Groundwater pumping in portions of the area is regulated by the Hudspeth County Underground Water Conservation District No. 1 and the Culberson County Groundwater Conservation District. Figure 4 presents the regulated areas of these districts in relation to the boundaries of the aquifers and the properties that may be involved in potential groundwater transfer projects. Outside of these districts, groundwater is regulated by the Rule of Capture.

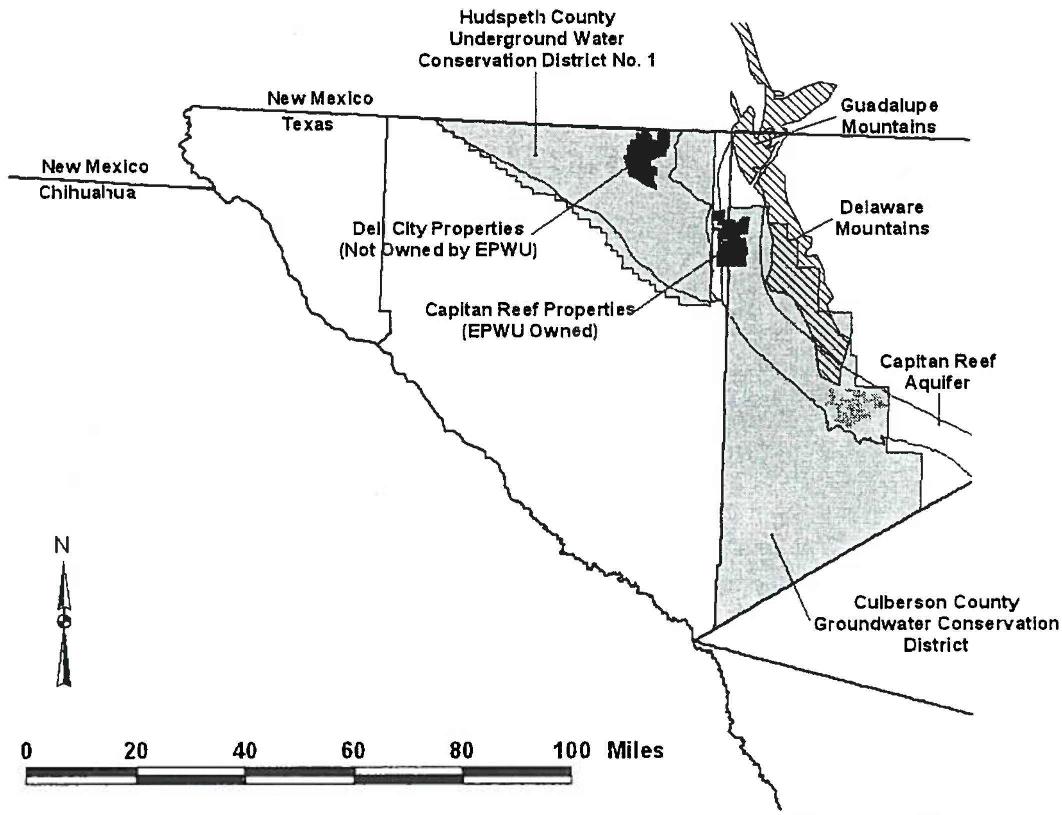


Figure 4. Location of Groundwater Conservation Districts in the Dell City Area

Because the Regional Water Plan contemplates a transfer of water from the Dell City area to El Paso County around 2030, El Paso Water Utilities (EPWU) has completed this study to better understand the potential groundwater yield of the area. This report is the product of that study and begins with a review of the hydrogeology of the area, including reviews of previous studies of the area related to groundwater occurrence and movement. The report also includes discussion of the development, calibration and application of three groundwater flow models of the area.

After a brief overview of the physiography, climate and geologic setting of the area (Section 2), this report presents a review of previous reports and studies that cover the geology and hydrogeology of the area (Section 3). The previous work provided the foundation to describe details of the hydrogeologic setting (Section 4) and the development of three alternative conceptual models of groundwater occurrence and movement that is summarized in Section 5. The development of the three finite-difference models (one for each conceptual model) is described in Section 6. Calibration of the three finite-difference models with publicly available groundwater elevation data from the Texas Water Development Board and the New Mexico Office of the State Engineer is described in Section 7. Section 8 summarizes model application using a total of 772 50-year simulations, which consider the three finite-difference models, various future climatic conditions, and alternative pumping scenarios.

The models cover the Bone Spring-Victorio Peak Aquifer in its entirety, and a portion of the Capitan Reef Aquifer. Past management approaches has assumed that the Capitan Reef and the Bone Spring-Victorio Peak Aquifers to be separate due to the Salt Basin playa that lies between the two named aquifers. One of the objectives of this modeling effort is to test that assumption.

This study and the resulting models were developed for the internal analyses of EPWU. A draft report and the model files were reviewed by Dr. Robert Mace of the Texas Water Development Board, Dr. G. F. Huff formerly of the United States Geological Survey, and Mr. Steve Finch of John Shomaker and Associates. A meeting of the reviewers was held on June 18, 2008 at the offices of EPWU to discuss comments to the report. The comment letters are provided in Appendix F, as well as responses to those comments.

This report and the model files have been forwarded to the Texas Water Development Board for their future use. As such, this report and the associated models are not official TWDB Groundwater Availability Models (GAMs). However, it is hoped that this effort will assist the TWDB in their development of GAMs for the area.

2.0 OVERVIEW OF DELL CITY/DIABLO PLATEAU STUDY AREA

2.1 Physiography

The Dell City area lies within the Trans-Pecos province of Texas, or the west-projecting part of the State between the Pecos River and the Rio Grande (King, 1965, pg. 11). The Trans-Pecos province is part of the Basin and Range physiographic province that extends from eastern California to west Texas. North-south trending mountain ranges and valleys, termed horsts and grabens, are the major characteristic of the Basin and Range province.

The watershed divide in the Hueco Mountains between the Otero Mesa and the Tularosa Valley bounds the study area on the west, and the watershed divide in the Guadalupe and Delaware Mountains bound the area on the east (Figure 5). The Sacramento Mountains represent the northern boundary, and also represent the source of most of the recharge to the aquifer system. The southern boundary is a combination of a watershed divide associated with the Baylor Mountains and a groundwater divide associated with the Babb Flexure and Bitterwell Break (Nielson and Sharp, 1985; Boyd and Kreitler, 1986; King, 1965; Goetz, 1977; all as cited by George and others, 2005, pg. 20).

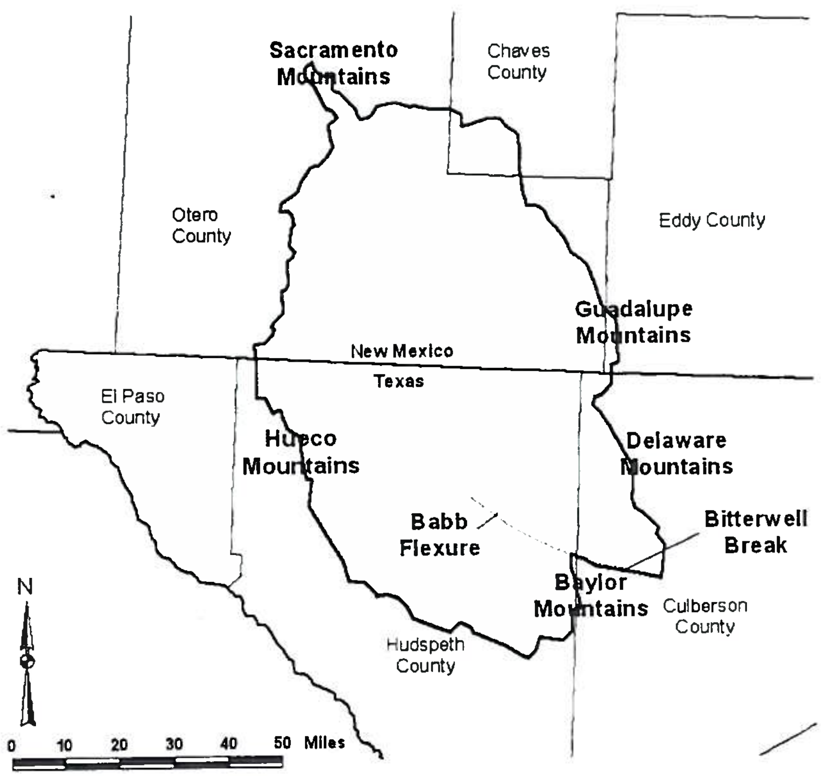


Figure 5. Watershed Divides and Southern Groundwater Divide

The study area is defined as the watershed area that drains into the Salt Basin-Crow Flats area, and can be viewed as three separate physiographic units that correspond to three different aquifer areas: 1) the upland area associated with the Otero Mesa and Diablo Plateau in the western portion of the study area, 2) the lower lying area of alluvium and playas associated with the Salt Basin and Crow Flats in the central portion of the study area, and 3) the upland area associated with the western slopes of the Guadalupe and Delaware Mountains in the eastern portion of the study area including the Capitan Reef Aquifer (Figure 6).

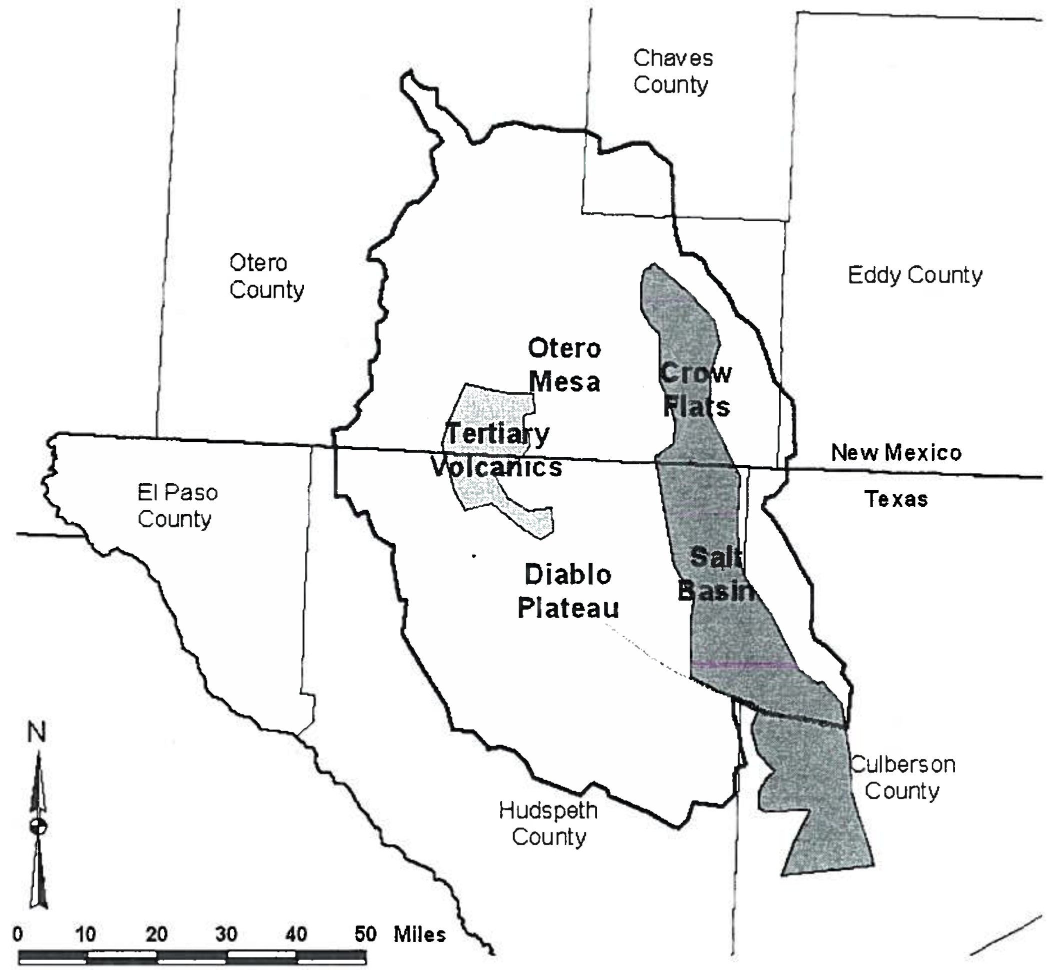


Figure 6. Physiographic Units

The Otero Mesa and Diablo Plateau is a continuous feature, but is named the Otero Mesa in New Mexico and the Diablo Plateau in Texas (Mayer, 1995, pg. 16). This portion of the study area gently slopes east, and drains toward a playa called Crow Flats in New Mexico and Salt Basin in Texas. Within the relatively flat plateau area, Tertiary-age volcanic intrusives (such as the Cornudas Mountains) form distinct and isolated landmarks that rise above the plateau.

Elevations of the plateau range from about 4,000 ft above mean sea level (amsl) to about 5,000 ft amsl on the plateau proper to over 9,000 ft amsl in the Sacramento Mountains. The peaks associated with the intrusives are at elevations up to about 7,200 ft amsl (Wind Mountain in New Mexico).

The area that lies in the central portion of the study area is lower lying and generally flat. In Texas, the area is called the Salt Basin, in New Mexico is known as Crow Flats (Mayer, 1995, pp. 16-19). This area receives drainage from several ephemeral streams that cross the upland areas on all sides and has no surficial outlet. Consequently, the area is characterized by playas that contain evaporite deposits. Elevations range from about 3,600 ft amsl to about 4,000 ft amsl. Bjorklund (1957, pg. 7) noted that sinkholes are common in this area, including one that was about 50 feet across and 10 feet deep. Bjorklund (1957, pg. 9) postulated that these features resulted from solution of gypsum in the valley fill and could be related to solution of the underlying limestone.

The eastern portion of the study area is the transitional area from the Basin and Range province to the Permian Delaware Basin (Sharp, 2001, pg. 44). The boundary between the Basin and Range province and the Delaware Basin is the Capitan Reef rocks that are exposed in the Guadalupe Mountains (Sharp, 2001, pg. 44). Due to the short distances between the playa area and the mountains to the east, the area is characterized by steep slopes with elevations ranging from about 4,000 ft amsl to over 8,700 ft amsl in the Guadalupe Mountains.

2.2 Climate

The study area lies within the Chihuahuan desert, and consequently the climate is arid. Summers are hot and dry. Winters are generally mild except for short periods of severe winter weather (Mayer, 1995, pg. 19). Brown and Caldwell (2001, pg 2-2) reported that average minimum temperature is approximately 25 degrees Fahrenheit (^{o}F), and the average maximum temperature in the summer is about 95 ^{o}F.

Precipitation has historically been measured at ten stations in the region. A summary table of the data is presented in Table 1, including the period of record for each station. The locations of these stations are presented in Figure 7.

As can be seen in Table 1, precipitation increases with increasing elevation. Also note that the Dell City station has a relatively short record. Figure 8 presents a plot of elevation vs. precipitation and a best-fit regression curve for all stations other than Dell City. Note that the adjusted r-squared value is 0.984 (ideal fit equals 1.000).

Table 1. Summary of Precipitation Data

Station Name	Code (Fig 7)	State	Elevation (ft amsl)	Average Precipitation (in/yr)	Number of Years with Complete Records	Period of Record
Alamogordo	AL	NM	4,350	11.28	58	1931-1997
Cloudcroft	CL	NM	8,660	28.44	47	1931-1997
Cornudas Service Station	CO	TX	4,480	9.43	40	1940-1997
Dell City 5 SSW	DC	TX	3,770	11.15	9	1979-1997
Elk 2	EL	NM	5,750	16.24	54	1931-1997
Mayhill	MH	NM	6,565	18.93	42	1931-1976
Mountain Park	MP	NM	6,780	19.38	53	1931-1997
Orogrande	OR	NM	4,182	10.33	71	1905-1997
Salt Flat	SF	TX	3,717	8.48	36	1945-1997
White Sands	WS	NM	3,995	9.03	51	1939-1997

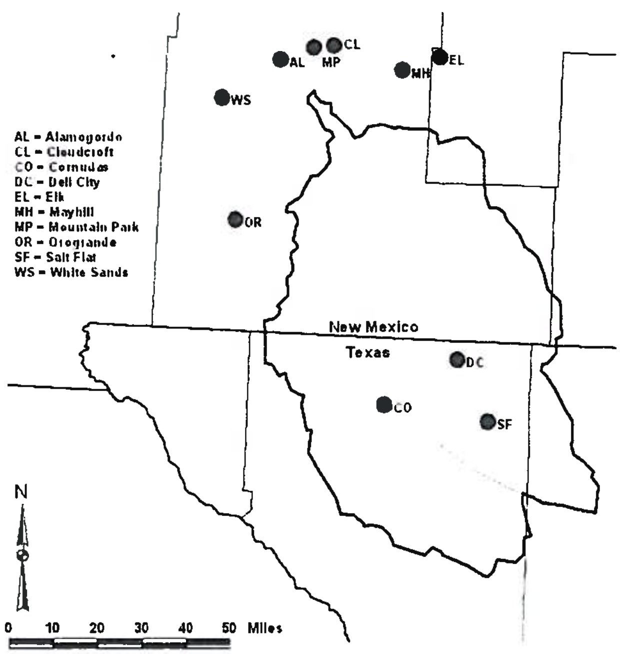


Figure 7. Location of Precipitation Stations

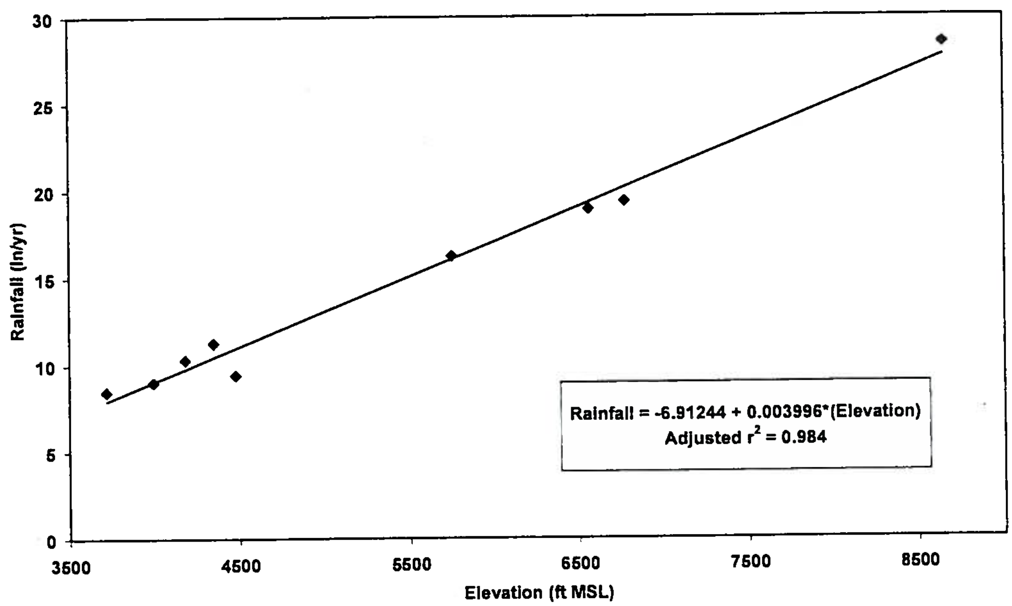


Figure 8. Elevation vs. Average Annual Precipitation

Mayer (1995, pp 19-23) presented a similar analysis, but included the Dell City station. The unadjusted r-squared value for this analysis was 0.952, and the period of record used was unclear.

Table 2 presents a summary of the annual precipitation data in terms of percent average. This is particularly useful information to evaluate data bias when considering potential changes in recharge due to wet periods and droughts.

Mayer (1995, pg. 23) cited Hydrosphere Data Products, Inc. (1992) regarding potential evaporation estimates. Annual potential evaporation ranges from 75 inches at high elevations to 98 inches at low elevations.

Table 2. Annual Precipitation Expressed as Percent of Average

Year	Alamogordo	Cloudcroft	Cornudas	Elk	Mayhill	Mountain Park	Orogrande	Salt Flat	White Sands	Average
1948				88.49	83.87	95.84	81.93	76.16		85.26
1949		112.05	142.32	120.57	135.53	105.02	98.68	130.74	132.56	122.18
1950	74.79	73.83			110.81	67.04	70.69	96.67	70.21	80.58
1951	72.05	81.95		55.97	45.42	86.55	40.58	39.14	40.09	57.72
1952	42.98		67.98	72.79	81.23	51.04	87.25	103.15		72.35
1953				55.11	52.61	88.35	58.20	54.11	55.15	60.59
1954	56.98	69.72	88.02	91.94	81.87	75.30	50.65	107.87	60.13	75.83
1955	92.70	94.33	87.49	109.06	92.48	98.31	110.11	96.08	80.62	95.69
1956	25.97	62.30	45.07	52.65	42.41	53.52	31.86	47.98	31.01	43.64
1957	118.13	97.14	66.28	113.12	118.10	108.02		89.01	109.41	102.40
1958	135.14	132.90	157.06	140.77	98.50	131.24			148.39	134.86
1959	95.53	74.04	73.60	64.23	78.12	68.28		46.68	43.85	68.04
1960	83.92	81.04	124.29	106.10	98.56	120.61			110.41	103.56
1961	100.14	107.72	56.10	79.37	89.00	134.44		55.64	83.83	88.28
1962	114.85	100.10	81.66	126.97	112.71	107.60	135.67	95.96		109.44
1963		85.93	79.65		78.64	89.18	91.03	105.87	66.67	85.28
1964	59.73	74.99	91.84	54.44	58.31		53.36	70.26	54.93	64.73
1965	115.38	119.29	81.24	86.39	113.71		81.83	76.51	96.79	96.39
1966	86.49		144.55	112.01	102.15	93.88	113.59	169.05	103.99	115.71
1967	96.15	91.52	76.46	70.51	102.20	88.56	110.98	101.97	78.18	90.73
1968	105.90	95.24	102.55	128.08	113.03		102.55	115.41	83.72	105.81
1969	125.66		89.19	116.32			93.26	117.30	115.84	109.59
1970	52.11		84.31	58.19	82.55		75.34	104.45	63.68	74.38
1971	109.89		84.84			106.52		114.12	91.69	101.41
1972			132.35	129.13	129.40	134.96		217.39	129.24	145.41
1973	97.48		110.08	63.86			85.03	89.60	74.09	86.69
1974	148.26		174.78		148.05				126.36	149.36
1975	98.63		117.61	92.31	75.69				67.88	90.42
1976	144.27		70.42			115.03			89.92	104.91
1977	92.52		85.05	73.16		88.51			86.38	85.12
1978				155.49		150.64	161.53		123.70	147.84
1979	123.80		65.43	111.15		103.16	103.33	111.64	103.88	103.20
1980	90.83	86.10				89.39	107.69	83.47		91.49
1981	111.30	102.56				102.60	110.79	159.74	102.88	114.98
1982	113.17		124.19			111.06	113.11		110.63	114.43
1983	109.27	102.77	86.01			123.03	107.78	90.89	109.19	104.14
1984	153.75	125.94	155.79	127.90		150.18	201.91	114.71	177.19	150.92
1985	162.53	126.43				146.77			158.91	148.66
1986	147.02	141.09		212.75		127.42	146.81		143.63	153.12
1987	104.92			86.58		98.11	125.60	140.76	130.45	114.40
1988	103.33	126.60		96.43			141.68		185.94	130.80
1989	98.28	93.91		85.84		77.00	88.51	97.73	92.14	90.49
1990	133.90	110.36	101.60	85.04		123.24	124.73	122.61	127.80	116.16
1991	164.65	137.96				136.56	195.04			158.55
1992	127.97	112.47	153.99	115.15		101.51			172.65	130.62
1993	113.08		95.77			109.67	91.32	106.10		103.19
1994	107.58	118.87	84.52	99.51					63.34	94.77
1995	81.79	88.49		101.30		114.88	122.99		93.02	100.41
1996	70.36	95.59		108.87		87.22	122.21		112.51	99.46
1997		110.61				129.23			121.48	120.44

2.3 Geologic Setting

Permian and Cretaceous limestones and basin fill of Quaternary age dominate the geology of the study area. Volcanic intrusives of Tertiary age are important local features in some areas. The study area has been subjected to a variety of geologic processes over time including deposition, uplift, faulting, salt dissolution, and volcanism (Sharp, 1989, pg. 123).

The geologic history of the study area has been described by Ashworth (1995), Bjorklund (1957), DeJong and Addy (1992a), DeJong and Addy (1992b), Dietrich and others (1995), Gates and others (1980), George and others (2005), Goetz (1977), King (1965), Kreitler and others (1990), Mayer (1995), Mullican and Mace (2001), Reed (1965), Scalapino (1950), Sharp (1989), Sharp (2001), Uliana (2001) and Urbanczyk and others (2001).

The important aquifers in the area are Permian formations (The Bone Spring-Victorio Peak aquifer and the Capitan Reef aquifer). The older Bone Spring-Victorio Peak limestones were shelf deposits. The younger Capitan Reef was a barrier reef that encircled the Delaware Basin. The Salt Basin is a graben that is filled with alluvial sediments. A generalized geologic cross section of the area is shown in Figure 9, and is taken from Ashworth (1995) as modified by George and others (2005, pg. 22). Although the Bone Spring-Victorio Peak aquifer and Capitan Reef Aquifer are separated by the playa deposits associated with the Salt Basin Graben as shown in Figure 9, there appears to be a hydraulic connection between the two named aquifers across the playa.

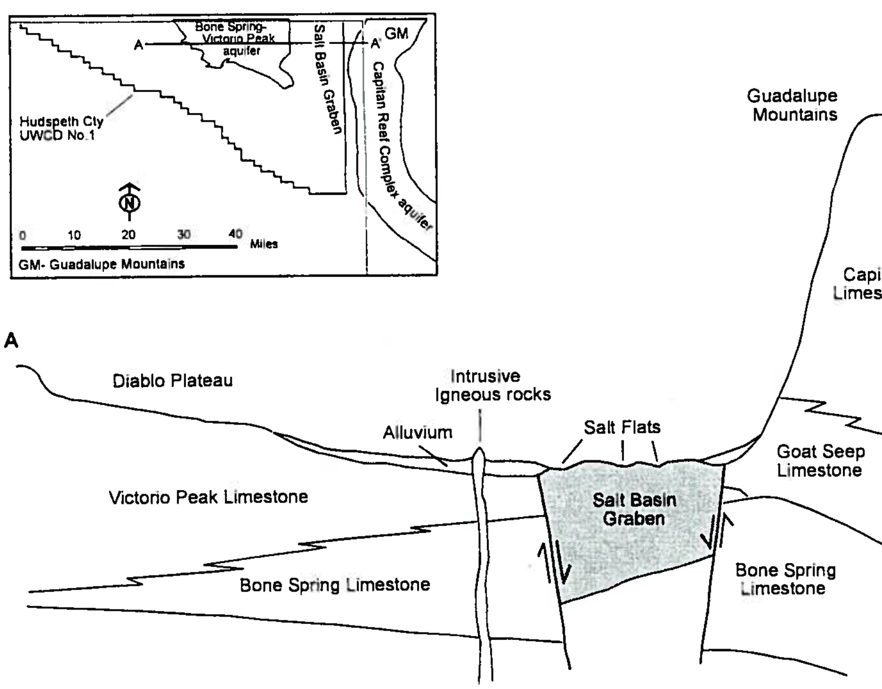


Figure 9. Generalized Cross-Section of Dell City Area
(from Ashworth, 1995 as modified by George and others, 2005, pg. 22)

3.0 PREVIOUS WORK

This section presents a review of previous studies, and is focused on summarizing significant work that was used to develop the conceptual model of groundwater flow, and specific data related to aquifer parameters, recharge and discharge. This review is covered in Sections 3.1 to 3.15. Section 3.16 summarizes previous studies that are important to the area, but were not available at the time of this work. Special thanks are due Steve Finch of John Shomaker and Associates who identified these studies during review of this report. Several of these reports that Mr. Finch provided were confidential work products until recently.

3.1 Scalapino (1950)

Scalapino (1950) completed the first investigation of the groundwater resources of the area, and was also the first to recognize that the recharge of the Dell City area was likely from Sacramento River flows that infiltrated into the aquifer system (Scalapino, pg. 6), but was not able to develop an estimate of the average annual recharge (Scalapino, pg. 8). Prior to 1947, groundwater development in the study area was limited to livestock watering and domestic supply of the few ranches in the area (Scalapino, 1950, page 1). From 1947 to 1949, there was a rapid increase in the use of groundwater for irrigation (Scalapino, 1950, pg.1). Scalapino (1950, pg. 7) estimated that total groundwater use in 1949 was 18,000 acre-feet.

Scalapino (1950, pg. 7) reported that 78 irrigation wells were constructed between 1947 and 1949. However, only 32 of the wells had yields that range from 350 to 3,000 gallons per minute. He presented several well records and logs (Scalapino, 1950, pp.10 to 33), and summarized depth-to-water measurements, including the flow of a naturally occurring spring (Scalapino, 1950, pp 34 to 37). Scalapino (1950, pg 7) noted that groundwater levels declined an average of 0.4 feet between March 1948 and February 1949, and an average of 0.36 feet between February 1949 and February 1950, which was concluded to be not a serious decline (Scalapino, 1950, pg. 8).

Scalapino (1950, pg. 9) noted that the area could likely sustain expansion, but identified that a large percentage of the wells yielded insufficient quantities of water for large-scale irrigation. He also noted that suitable areas were limited on the east by the playa and on the west by an "indefinite line beyond which the depth to water is too great for economical pumping".

3.2 Bjorklund (1957)

Bjorklund (1957) completed an investigation that was similar in scope to Scalapino (1950), but focused on the Crow Flats area of New Mexico. Bjorklund (1957, pp 11-12) noted that in the southern portion of the Crow Flats area, the groundwater gradient is "remarkably flat and almost level". He noted that the principal reason for the flat gradient was the "unusually high permeability of the water-bearing materials, especially the Bone Spring limestone with its many solution channels" (Bjorklund, 1957, pg 12). Based on his analysis, Bjorklund (1957, pg 12) concluded that these "solution channels are interconnected and belong to a common hydraulic system".

Bjorklund (1957, pp 12-14) evaluated the changes in groundwater elevation due to irrigation pumping. He noted that the groundwater elevation in Well 81 (as designated by Scalapino, 1950) declined about 13 feet from 1948 to 1955 largely as a result of increased groundwater pumping in the area (Bjorklund, 1957, pg 14). However, Bjorklund (1957, pg 14) reported:

> *Many residents report that there has been no decline in water levels because their wells are just as productive as they ever were. Evidently aquifer yields to many wells are so great and drawdowns are so small that a few extra feet of pumping lift goes unnoticed.*

Bjorklund (1957, pg 14) provided some anecdotal information on the mechanism of recharge to the groundwater system. Based on observations of residents, runoff from the higher elevations infiltrates into the canyon floors and bajadas. Water that reaches the valley floor often drains into the various sinkholes. According to local residents, many floods in the various arroyos are dissipated before reaching the playa area.

Bjorklund (1957, pp 15) estimated that recharge to the aquifer system is "probably less than 100,000 acre-feet annually" based on the following:

1. Under pre-development conditions, the lateral movement of groundwater was through the limestone and the discharge of the groundwater was from the playa
2. By 1955, groundwater elevations had declined to the point where the movement of groundwater from the limestone to the playa had ceased or possibly reversed.
3. Given this condition, groundwater elevations would remain constant if discharge by pumping was equal to recharge
4. During 1955, pumping was about 100,000 acre-feet per year and groundwater elevations in the limestone continued to decline.
5. This decline in groundwater elevations suggested that pumping was greater than recharge, and total recharge, therefore is less than 100,000 acre-feet per year.

Bjorklund (1957, pg 14 and 15) noted that the groundwater pumping caused declines in groundwater elevations sufficient to dry up Crow Spring that was noted as a flowing about 3 gallons per minute by Scalapino (1950, pp 20-21).

3.3 Reed (1965, 1973, 1980)

Reed (1965) prepared a report that evaluated the groundwater resources of the Diablo Farms area that overlies the Capitan Reef limestone and Goat Seep limestone. Reed (1973) and Reed (1980) represented updates of this original report. Reed (1965, pg 5) noted that the groundwater in the Diablo Farms area occurs in both near-surface alluvial materials and in the underlying Capitan Reef and associated formations. The groundwater generally moves west, towards the Salt Basin (Reed, 1965, pp. 5-6). Reed (1965, 1973 and 1980) provided data related to well and test-hole drilling, groundwater levels and results of pumping tests of the aquifer system.

Reed (1965, pp 11-12) concluded that, based on an analysis of groundwater elevation gradients, the faulting in the area that is characteristic of the Basin and Range setting and defines the boundary between the Salt Basin graben and upland limestone area, has "enhanced the development of porosity and permeability" of the limestone, and has not acted as a barrier to movement into the Salt Basin.

Based on a Darcian calculation, Reed (1965, pg 18) estimated that the recharge to the area above a depth of 700 feet is about 15,400 acre-feet per year. The recharge to this area is from rainfall on the outcrop of the Capitan Reef and runoff that infiltrates the alluvium and ultimately the reef where the two are hydraulically connected (Reed, 1965, pg 17). Based on this estimate and an analysis of groundwater elevation changes, Reed (1973, pg 1) estimated that irrigation pumping in the Diablo Farms area of between 25,000 to 35,000 acre-feet per year would result in annual groundwater elevations declines of up to 2 to 3.5 feet.

3.4 Parizek (1979)

Parizek (1979) completed a report for the Soil Conservation Service that developed recommendations for floodwater recharge wells. This investigation focused on interpreting aerial photographs and satellite images to map fracture traces and lineaments (Parizek, 1979, pg. 10). Due to documented variation in well yields (e.g. Scalapino, 1950), Parizek (1979, pg 5) hypothesized that a well located along fracture trace and/or lineament intersection would prove significantly more productive when compared with randomly located wells. It was on this basis that recommendations were developed for locating recharge wells.

Parizek (1979, pp. 5 and 8, and Figure 2) presented data related to predicting the probability of obtaining a particular specific capacity in a well. This analysis was based on thirty-three control points. It was noted that the available data are likely biased in favor of "successful wells" (Parizek, pg 8).

3.5 Gates and Others (1980)

Gates and others (1980) completed geophysical surveys in the southern end of the study area. Based on this investigation, the areas covered by the Goat Seep limestone and Capitan Reef were delineated (Gates and others, 1980, Figure 2). Gates and others (1980, pg. 18) also provided specific capacity data.

Gates and others (1980, pg 33) updated estimates of pumping and irrigated acreage in the Dell City area, and reported that groundwater elevations in the Dell City area declined about 30 to 40 feet between 1948 and 1972. The pumping and irrigated acreage data are summarized in Table 3.

Table 3. Estimates of Pumping and Irrigated Acreage in the Dell City Area (from Gates and others, 1980)

Year	Pumping Estimate (AF/yr)	Irrigated Acres	Source
1960	100,000	25,000	Davis and Leggat, 1965
1967	105,000	N/A	Davis and Gordon, 1970
1972	100,000	N/A	Gates and others, 1980
1974-76	N/A	40,000 to 42,000 (Texas)	Gates and others, 1980
1974-76	N/A	5,000 to 6,000 (New Mexico)	Gates and others, 1980

3.6 Kreitler and others (1990)

Kreitler and others (1990, pg 51) noted that the aquifer containing fresh water in the Diablo Plateau may be extremely thick and cited an 1,800 ft deep Soil Conservation Service test hole that was drilled on the northeastern side of the plateau that never reached brackish water. It was also noted that the aquifer is extremely transmissive and noted that pumping in the Dell City area was approximately 98,500 acre-feet per year for 30 years with only 33 ft of drawdown.

Kreitler and others (1990, pg. 51 and Figure 2) reported that groundwater flow on the Diablo Plateau is predominately southwest to northeast, and that there is a groundwater divide close to the southern edge of the Diablo Plateau. The gradient for the Diablo Plateau aquifer is approximately 5 ft/mi, a relatively low gradient considering the 1300 ft of topographic relief in the same area (Kreitler and others, 1990, pg. 51). The low gradient was also evidence of high transmissivities, and the pumping in the Dell City area was assumed to not impact regional groundwater flow due to these high transmissivities (Kreitler and others, 1990, pp. 51 and 54).

Kreitler and others (1990, pg. 54) stated that recharge occurs over the entire area of the plateau, and that the catchment area is about 2,900 square miles. Based on soil chloride concentrations, it was postulated that the recharge likely occurs during flooding of the arroyos that drain the plateau. Fractures that are typically concentrated in the arroyos permit surface water to move rapidly through the thick unsaturated zone (Kreitler and others, 1990, pg. 54).

3.7 Ashworth (1995)

Ashworth (1995, pg. 1) described the groundwater resources underlying the irrigable land of the area (i.e. the Bone Spring-Victorio Peak Aquifer as designated by the Texas Water Development Board). Ashworth (1995, pg 5 and Figure 3) updated estimates of irrigated acreage and total pumping. These results are summarized in Table 4.

Table 4. Estimates of Irrigated Acreage and Total Pumping
From Ashworth (1995)

Year	Irrigated acreage	Pumped Water (AF/yr)
1958	19,000	65,000
1964	29,000	90,000
1969	20,000	85,000
1974	33,000	130,000
1979	39,000	144,000
1984	19,000	100,000
1989	20,000	95,000

Ashworth (1995, pg 13) reviewed literature associated with recharge to the aquifer system, and evaluated total pumping with the groundwater level in an observation well equipped with a continuous recorder. It was noted that pumping rates of between 40,000 and 60,000 AF/yr resulted in groundwater level rises, and when pumping was between 90,000 and 100,000 AF/yr, groundwater levels remained relatively constant. Based on this observation, 90,000 to 100,000 AF/yr was considered a "reasonable estimate of total annual recharge to the aquifer, which includes both lateral inflow and irrigation return flow".

Ashworth (1995, pg. 23) characterized the groundwater quality as brackish, very hard, and dominated by elevated levels of calcium, sodium, sulfate and chloride. Ashworth (1992, pg. 29) reported that in a 30-well survey of groundwater quality in 1992, the total dissolved solids ranged from 1,148 mg/l to 6,533 mg/l, and averaged 3,530 mg/l. The high total dissolved solids require increased pumping to leach accumulated salts from the root zone.

Ashworth (1995, pg. 35) reported that groundwater quality has been changing since the 1940s when irrigation began:

> *Water applied to agricultural land has percolated down to the water table, leaching additional minerals on its way. Also, the drilling and open completion of hundreds of wells in the valley has created a condition in which zones containing poor-quality water can mix with all other water bearing zones.*

The total dissolved solids in Well 48-07-205 between 1948 and 1992 increased from 1,119 mg/l to 4,395 mg/l (Ashworth, 1995, pg. 35). The most recent sample (June 27, 2001) from this well had a total dissolved concentration of 4,305 mg/l. The database of water quality in wells in the area is maintained by the Texas Water Development Board, and is accessible at:

http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/GWdatabaserpt.htm

3.8 Mayer (1995)

Mayer (1995, pg. 2) evaluated the role of how regionally pervasive fractures affect regional groundwater flow. Mayer (1995, pp 2 and 3) completed this evaluation by characterizing the hydrogeology and regional fracture system of the aquifer system in the Otero Mesa-Diablo Plateau area. He also constructed a two-dimensional, steady state numerical model of the area to test various scenarios of permeability trends and regional fracture anisotropy (Mayer, 1995, pg. 2 and 117).

Mayer (1995, pg 117) simulated the aquifer system as an equivalent porous medium. As stated by Mayer (1995, pg 117):

> *Fractures are assumed to be numerous enough and distributed evenly enough for the effects of individual fractures to be ignored. Thus, transmissivity is modeled as a bulk property of the aquifer and no account is taken of individual fracture contributions or fracture properties such as aperture, roughness, or length. Given the size of the area and the numerous, widely distributed fractures, this appears to be a reasonable assumption (Long and others, 1982).*

Mayer (1995, pg 118) assumed a constant aquifer thickness. He also noted that thickness is accounted for in the transmissivity term, and that constant thickness was a reasonable assumption given the depositional environment of the aquifer where paleo-relief was minimal during the Permian.

The model was bounded on the west and north by surface water divides. The boundary on the south was a symmetry boundary where regional flow is to the east, parallel with the boundary. The boundary on the east was a combination of a symmetry boundary where westward flow from the Guadalupe Mountains and eastward flow from the Otero Mesa converge and a constant head boundary that corresponds to the water table in the Salt Basin playa (Mayer, 1995, pp. 120 and 121).

Five transmissivity zones were defined based on fracture density and fracture orientation (Mayer, 1995, pg. 122). Each domain was assigned an internally constant transmissivity (i.e. transmissivity within each zone was constant). The transmissivity for each zone that contained limestone was constrained by values collected in the literature for other carbonate aquifers, and the alluvial areas were constrained by literature values of granular aquifers (Mayer, 1995, pg. 122). Adjustments to these transmissivity values were made in the model calibration process (Mayer, 1995, pp 118 and 122).

Mayer (1995, pp 125 to 132) presented estimates for recharge and discharge components. Recharge was assumed to consist of precipitation over all but the lowest elevations of the study area, and generally followed the method described by Maxey and Eakin (1949), where recharge increases with elevation. At lower elevations, Mayer estimated recharge based on soil chloride profiles as reported by Kreitler and others (1990). Discharge from the system was assumed to consist of irrigation pumping and evaporation from the Salt Basin Playa (Mayer, 1995, pg. 125). Interbasin flow in the southeast portion of the study area, livestock pumping and domestic pumping were assumed negligible (Mayer, 1995, pg. 125).

Mayer (1995, pg 126) estimated each component of recharge and discharge. Distributed recharge using both the Maxey-Eakin method and the soil chloride profiles yielded an estimate of 58,370 AF/yr. Although not mentioned in the text, the estimate for irrigation return flow was presented as a range (between 29,996 and 42,156 AF/yr). Therefore, total recharge was assumed to be between 88,366 and 100,527 AF/yr.

Discharge from pumping was estimated to be 81,070 AF/yr. Pumping was input as a rate in five model nodes (Mayer, 1995, pg. 187). Since the model estimated playa evaporation through constant head boundary conditions, it was not an input to the model, but an output. If the pumping is held fixed, and the playa evaporation is estimated as a residual in the simple water balance of the area (assuming no change in storage), playa evaporation is between 7,296 and 19,457 AF/yr.

Mayer (1995, pp. 132 to 138) used the model to test three configurations of transmissivity. Recharge and discharge were set and were not adjusted during calibration. Transmissivity was adjusted by trial and error in order to match the observed potentiometric surface. These simulations and results are summarized in Table 5.

Table 5. Summary of Mayer (1995) Simulations

Scenario	**Transmissivity (ft^2/day)**	**Fit to Observed Potentiometric Surface**	**Citation**
Homogenous and Isotropic	2940	"Serious, fundamental disagreements between observed and modeled cases"	Mayer (1995, pg.133)
Heterogeneous and isotropic	93 to 9300	"Much better match to the observed potentiometric surface"	Mayer (1995, pg. 136)
Heterogeneous and anisotropic	93 to 9300 with a 10:1 anisotropy ratio	"Adding anisotropy does not significantly change the model output"	Mayer (1995, pg. 138)

The overall conclusion of these simulations was that anisotropy is not a major factor in the configuration of the potentiometric surface because the coincidental alignment of the hydraulic gradient is nearly parallel to the major axis of transmissivity (Mayer, 1995, pg. 138).

The results on model fit are limited to the qualitative statements summarized above. No quantitative results are provided that allow for the evaluation of the model-estimated heads with observed groundwater elevations. Moreover, only steady state simulations were completed and therefore, storage change was assumed to be zero.

It was noted by Mayer (1995, pg. 122) that the most heavily fractured area was assigned a transmissivity of 9,300 ft^2/day. This value is more than an order of magnitude less than the highest values that were cited in the literature (Mayer, 1995, pg. 122). Given the modeling approach taken, it is likely that if the transmissivity values were adjusted higher to be consistent with the highest end of the literature values and recharge was adjusted upward commensurately, an equally good calibration would be achieved. Conversely, if transmissivity values were adjusted lower, an equally good calibration could be achieved with lower estimates of recharge.

3.9 Hibbs and Others (1997)

Hibbs and others (1997) compiled groundwater data for the transboundary region of Texas, New Mexico, and Chihuahua, and published a map of groundwater elevations in the Dell City area based on these data. The groundwater elevation contours are shown in Figure 10.

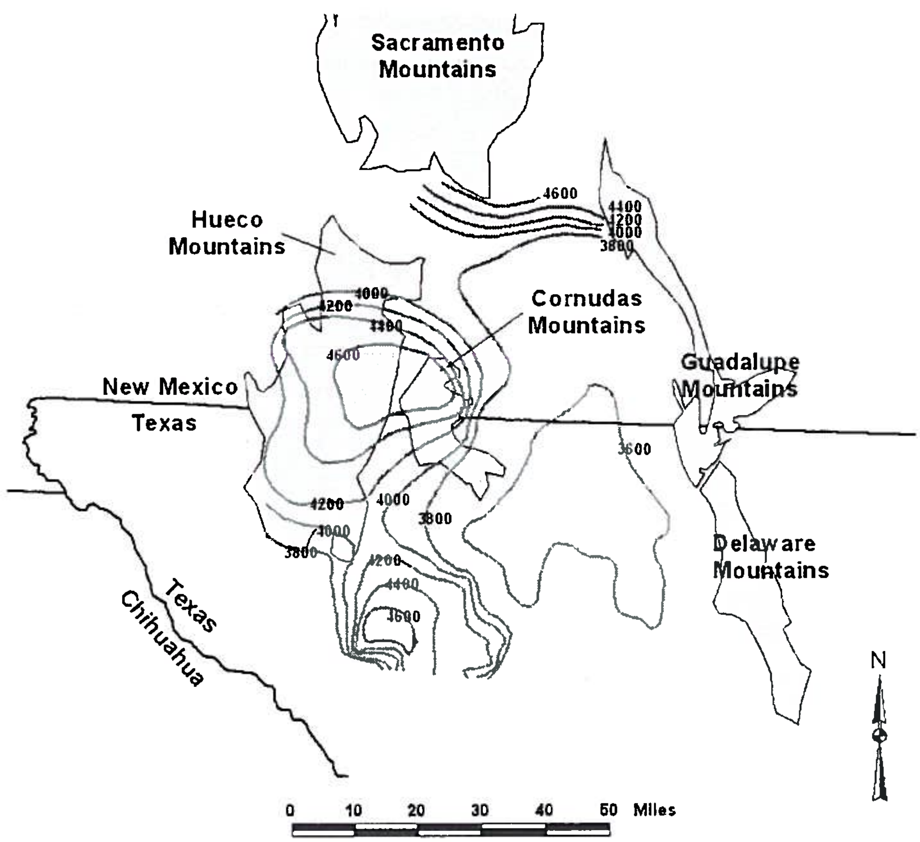


Figure 10. Groundwater Elevation Contours in the Dell City Area
(contours from Hibbs and others, 1997)

3.10 Brown and Caldwell (2001)

Brown and Caldwell (2001, pg. 1-1) summarized the findings of a water resource investigation of the O'Ban and Layton Farms. The investigation focused on obtaining site-specific information and data by completing well video surveys, well production evaluations, zonal water quality analyses, and aquifer testing (Brown and Caldwell, 2001, pg. 3-1). Estimated transmissivities ranged from 41,200 to 87,200 ft^2/day on the Layton Farm and ranged from 336,500 to 448,600 ft^2/day on the O'Ban Farm (Brown and Caldwell, 2001, pg. 3-3). Since the tested wells were current irrigation wells, it seems appropriate to assume that the estimated transmissivities are likely at the higher end of regional transmissivities.

3.11 Blair (2002a, 2002b)

Blair (2002a) developed estimated consumptive irrigation requirements for irrigated cropland within the boundaries of HCUWCD for the year 2001. Based on estimated acreage of cropland actually irrigated (27,000 acres out of 28,803 acres classified as farmland), and an average duty of cropland on CLM property (4.0 AF/acre), estimated pumping for 2001 was 108,000 AF. Further assuming an irrigation return flow of 30% of the total pumping (32,400 AF), the total consumptive water use was estimated to be 75,600 AF. The estimated consumptive irrigation requirement was then estimated as 2.8 AF/acre by dividing the total consumptive use (75,600 AF) by the total estimated irrigated acreage (27,000 acres) in the area.

Blair (2002b) presented data and information regarding alternative estimates of recharge to the area. John Ashworth had reviewed data and information subsequent to publication of Ashworth (1995). The results of this review were included in Blair (2002b, pg. 21). Ashworth's reinterpretation was that because historical pumpage from 1964 to 1989 was primarily flood irrigation, an average application of 80 inches per year (6.6 AF/acre) was appropriate, and irrigation rates from 1994 and 2000 was 60 inches (5.0 AF/acre) and 48 inches (4.0 AF/acre) due to the installation of sprinkler irrigation systems in the area. Based on these alternative assumptions, the method applied in Ashworth (1995, pg. 13) was revisited, and John Ashworth concluded that natural recharge could be as high as 160,000 to 200,000 AF/yr.

3.12 Groeneveld and Baugh (2002)

Groeneveld and Baugh (2002) completed analyses of satellite images to develop estimates of evapotranspiration from groundwater-irrigated agriculture and playa discharge. This work was completed for EPWU in support of this modeling effort, and the entire report is presented in this report as Appendix E. Landsat satellite data from 1974 to 2002 were used as the base data for the analysis.

Irrigation in the area averaged 21,353 acres for the period, with the maximum of 33,656 acres in 1975, and the minimum of 12,585 acres in 1994 (Groeneveld and Baugh, 2002, pg. 15). The estimated irrigated area for 1975 (maximum area during the study period) is presented in Figure 11.

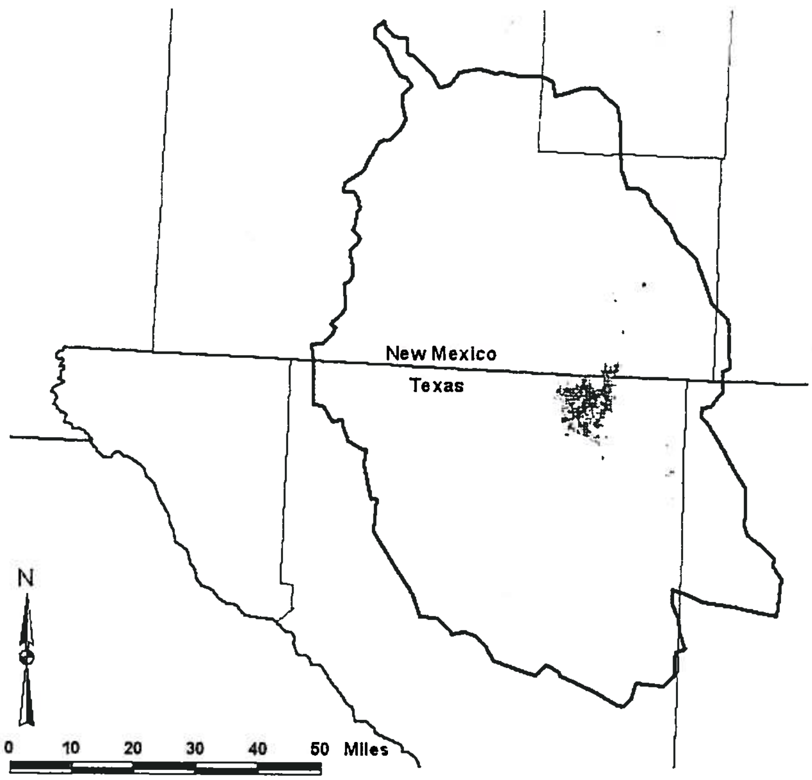


Figure 11. Estimated Irrigated Area in 1975
(from Groeneveld and Baugh, 2002)

Irrigation requirements were estimated using a Blaney-Criddle approach for alfalfa during a normal year, less average annual precipitation (Groeneveld and Baugh, 2002, pg.11). Based on this analysis, the irrigated acreage was multiplied by the estimated irrigation requirement of 3.859 ft/yr to yield a maximum pumping estimate of 129,877 AF/year for 1975 and a minimum pumping estimate of 48,567 AF/yr for 1994 (Groeneveld and Baugh, 2002, pg. 16). Confidence intervals for these acreage estimates were estimated to be between 13 to 20% depending on the number of satellite images used for mapping the year (Groeneveld and Baugh, 2002, pg. 15).

Playa discharge was estimated for eight years between 1984 and 2002. The average rate of discharge was 27,430 acre feet/year with a minimum of 12,176 acre feet/year in 2001 and a maximum of 44,089 acre feet/year during 1988 (Groeneveld and Baugh, 2002, pg. 20). Details of estimated playa discharge are presented in Chapter 4.7 of this report. Because of a lack of actual calibration data, Groeneveld and Baugh (2002, pg. 22) estimated that the confidence interval for this analysis is conservatively large at 100% (pus/minus 50%). The area of playa discharge for 1988 is presented in Figure 12.

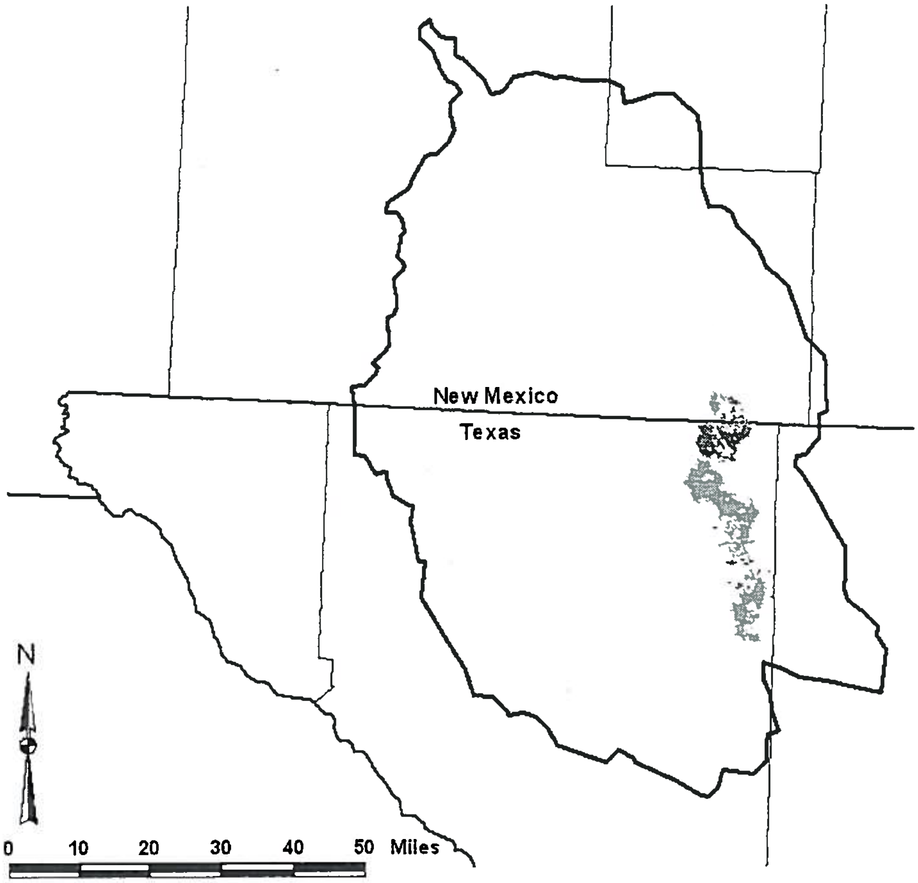


Figure 12. Estimated Area of Playa Discharge in 1988
(from Groeneveld and Baugh, 2002)

3.13 George and Others (2005)

George and others (2005) summarized and reviewed previous work related to the hydrogeology of Hudspeth County, Texas, summarized the groundwater management approach taken by the Hudspeth County Underground Water Conservation District No. 1, reviewed and summarized water demands in the area, and provided an assessment on water availability and supply.

George and others (2005, pg. 19-22) detailed a recommendation to expand the boundaries of the Bone Spring-Victorio Peak Aquifer, and stated that the new boundary would be recommended for approval in the 2007 State Water Plan. The recommended change was adopted in the 2007 State Water Plan. The figure from George and others (2005) is shown in Figure 13.

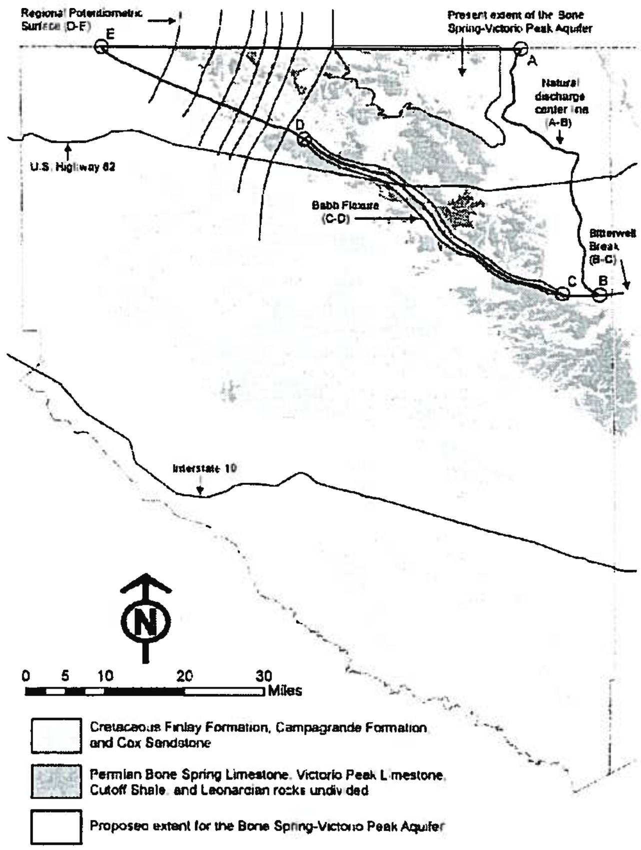


Figure 13. Proposed New Boundary for the Bone Spring-Victorio Peak Aquifer (from George and others, 2005, pg. 21)

3.14 Eastoe and Hibbs (2005)

Eastoe and Hibbs (2005) conducted stable and radiogenic isotopic sampling of wells in the Sacramento Mountains (extending between Cloudcroft and Crow Flats, New Mexico) and stable isotope sampling the Dell City area (Texas). Their findings (Figure 14) suggested that the isotopic signature of groundwater in the Texas portion of the Dell City area is different from the isotopic signature of groundwater in the area between Pinon (at the base of the Sacramento Mountains) and Crow Flats (north of the New Mexico-Texas state line). Furthermore, the isotopic signature of groundwater in the Texas portion of the Dell City area is similar to that of least-evaporated groundwater in the Diablo Plateau located to the south and west of Dell City, represented by groundwater from the east side of the Hueco Bolson where recharge is from the Diablo Plateau. This suggests that a significant amount of groundwater flows from the Diablo Plateau (probably from the Cornudas Mountains) to the Texas part of the Dell City area.

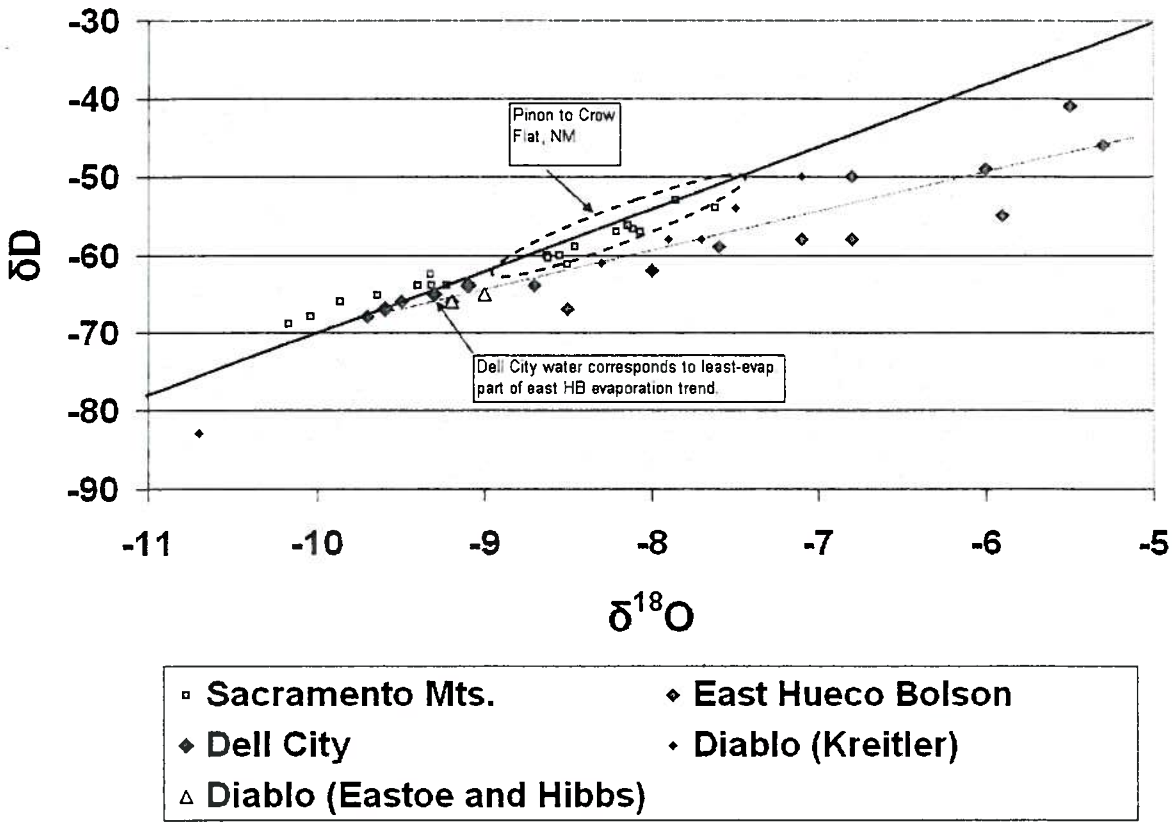


Figure 14. Oxygen and Hydrogen Isotopic Analyses from Eastoe and Hibbs (2005)

3.15 Huff and Chace (2006)

Huff and Chace (2006) provided "a synopsis of the current state of knowledge and understanding of the hydrogeology of the Salt Basin" and offered "possible areas of future study". The analysis was focused on the New Mexico portion of this study area, and used the term "Salt Basin" for the study area.

Of note in Huff and Chace (2006) were the groundwater elevation contour map (shown below as Figure 15) and a series of hydrographs (Figure 9 in Huff and Chace, 2006) that presented the relative change in groundwater elevations in New Mexico as a function of distance from Dell City. In summary, Huff and Chace (2006) demonstrated that groundwater elevations have decreased more in New Mexico wells closer to Dell City than in wells further away from Dell City.

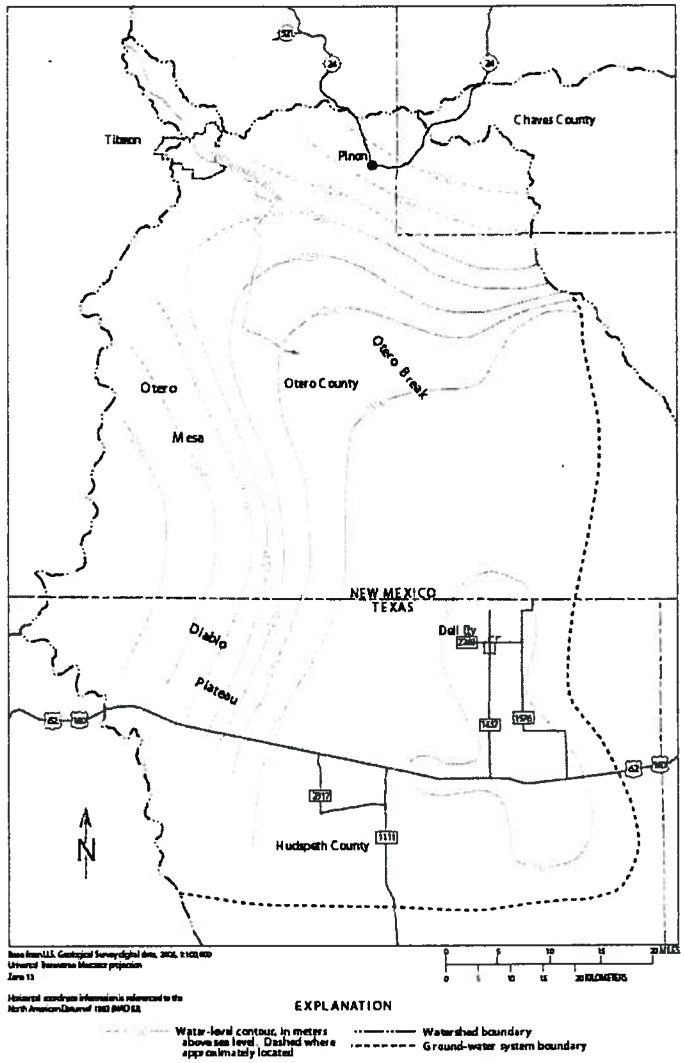


Figure 15. Groundwater Contours (from Huff and Chace, 2006)

Seven tasks were identified for future study (Huff and Chace, 2006, pg. 13-14):

1. Quantify the rate of recharge to the Salt Basin
2. Quantify the rates of discharge, both natural and anthropogenic, leaving the Salt Basin
3. Quantify the volume of groundwater in storage in the New Mexico part of the Salt Basin
4. Quantify the volume of recoverable groundwater in storage in the New Mexico portion of the Salt Basin

5. Identify areas of the carbonate aquifer that may be vulnerable to the introduction and rapid movement of subsurface contaminants
6. Establish the distribution of water quality in the New Mexico part of the Salt Basin
7. Develop a numerical ground-water-flow and transport model for the entire Salt Basin

3.16 Other Studies Made Available During Review

These reports were made available after completion of the review draft of this report. Although not used in model development, they are useful to check model performance and calibration.

3.16.1 Livingston Associates and John Shomaker & Associates (2002)

Livingston Associates and John Shomaker & Associates (2002) prepared the Draft *Tularosa Basin and Salt Basin Regional Water Plan 2000 – 2040* (Plan) for the South Central Mountain Resource Conservation and Development Council, Inc., (RC&D) through a grant from the New Mexico Interstate Stream Commission (ISC).

Livingston Associates and John Shomaker & Associates (2002, pg 6-15) estimated that the "watershed yield" of the Salt Basin region is 35,078 AF/yr, with approximately one-half originating from the Sacramento River. Due to the rock type (solutioned limestone), most all of the 35,078 AFY infiltrates into the ground water system and can be considered as recharge.

Livingston Associates and John Shomaker & Associates (2002, pp. 6-56 and 6-57) estimated "sustainable yield" in the Salt Basin as the summation of the watershed yield and the available ground water in storage with a total dissolved solid (TDS) range of less than 3,000 mg/L withdrawn at an equal rate over a 100 year period. Note that part of the "sustainable yield" includes a groundwater mining component over a 100-year period. Based on this definition, "sustainable yield" in the New Mexico portion of the Salt Basin was estimated to be 150,378 AF/yr.

3.16.2 Finch (2002)

Finch (2002) completed a groundwater model for the New Mexico Interstate Stream Commission. This effort had previously been a confidential report, and was provided during Mr. Finch's review of this effort. Mr. Finch stated that his 2002 report had only recently been released to the public. The objective of Finch (2002, pg. 3) was to evaluate the potential for developing groundwater from deep wells in the New Mexico portion of the Salt Basin. The groundwater flow model that was developed as part of this effort addressed issues related to well capacity, aquifer sustainability and pumping effects.

Finch (2002, pg.13) estimated hydraulic conductivity to be 100 ft^2/day in the Otero Break portion of Crow Flats and Dell City. Hydraulic conductivity for other areas ranged from 0.05 to 10 ft^2/day. Storativity for the region was estimated to be range from 0.05 to 0.15 for the unconfined areas of the model domain. Specific storage in the confined areas was estimated to be 1E-06 ft^{-1}.

Historic pumping estimates for used in the modeling effort are summarized in Table 6. New Mexico pumping estimates are for "groundwater diversions" for irrigation, and Texas pumping estimates are for "groundwater diversions" and assumed 50 percent return flow.

Table 6.Summary of Pumping Estimates from Finch (2002, pp 17 and 18)
All Pumping Estimates in AF/yr

Period	New Mexico	Texas	Total
1945 to 1960	2,552	33,154	35,706
1960 to 1969	12,709	42,080	54,789
1970 to 1979	14,494	49,730	64,224
1980 to 1989	14,494	70,133	84,627
1990 to 2000	14,494	49,730	64,224

Finch (2002, pg.15) estimated that the steady-state model recharge flux is 54,943 AF/yr, and noted that the estimate compared well with the estimate of Mayer (1995). The inflow amount includes an estimated inflow of 7,954 AF/yr from Penasco Basin, at the northern end of the study area.

3.16.3 Finch and Bennett (2002)

Finch and Bennett (2002) completed a preliminary hydrogeologic analysis of the northern part of Culberson County. The objective of this effort was to assist the Culberson County Groundwater Conservation District in the development of "an accurate understanding of the aquifers and their hydrogeologic properties, as well as a quantification of resources for building a foundation for sound planning measures".

Finch and Bennett (2002, pg. 11) estimated that the potential recharge for the Salt Basin sediments and Capitan Reef aquifer in Culberson County is 20,300 AF/yr, with most all of the water originating from the Guadalupe and Delaware Mountains.

Finch and Bennett (2002, pg. 17) constructed maps of groundwater elevation decline (1960 to 1995) contours of their study area, and identified two areas of significant decline: 1) Diablo Farms area and salt flat area north of the Baylor Mountains. Finch and Bennett (2002) were not able to conclude if the groundwater elevation declines in the Diablo Farms area are, in part, due to pumping in the Dell City area.

4.0 HYDROGEOLOGIC SETTING

4.1 Hydrostratigraphy

A simplified stratigraphic column is presented in Table 7. The oldest rocks of hydrogeologic significance are Permian in age (Sharp, 1989, pg. 123). The Permian rocks in the area are divided into three series: Wolfcamp, Leonard and Guadalupe. In general the Guadalupe series are high permeability shelf margin and reef deposits, the Leonard and Wolfcamp are variably permeable shelf facies (Sharp, 1989, pg. 124). The Capitan Reef and Goat Springs Limestone are of Guadalupe age. The areally extensive Bone Spring and Victorio Peak Limestones are of Leonard age.

Table 7. Simplified Stratigraphic Column – Dell City Area

System	Series	Formation
Quaternary		Alluvium Evaporites
Tertiary		Intrusive Igneous Rocks
Unconformity		
Cretaceous	Lower Cretaceous	Campagrande Limestone
Major Unconformity		
Permian	Guadalupe	Capitan, Goat Seep, San Andres
	Leonard	Victorio Peak, Bone Spring, Yeso
	Wolfcamp	Hueco
Pennsylvanian to Precambrian		Undifferentiated

From: Dietrich and others (1995), King (1965), Mayer (1995)
O'Neill and others (1998), Uliana (2001)

The Cretaceous rocks in the area are limited in thickness and do not represent important aquifers. Sharp (1989, pg. 127) noted that Kreitler and others (1987) suggested that a perched water table occurs within Cretaceous limestone in the southwest portion of the Diablo Plateau, and that the steep gradient implied that there is a lower hydraulic conductivity than in the underlying Permian limestone aquifer.

The Tertiary intrusives in and around the Cornudas Mountains are important features in that they represent a possible partial barrier to groundwater flow. O'Neill and others (1998) presented a schematic diagram of the area around the Cornudas Mountains that provides some insight to the position and thickness of these intrusives. This fence diagram is reproduced as Figure 16.

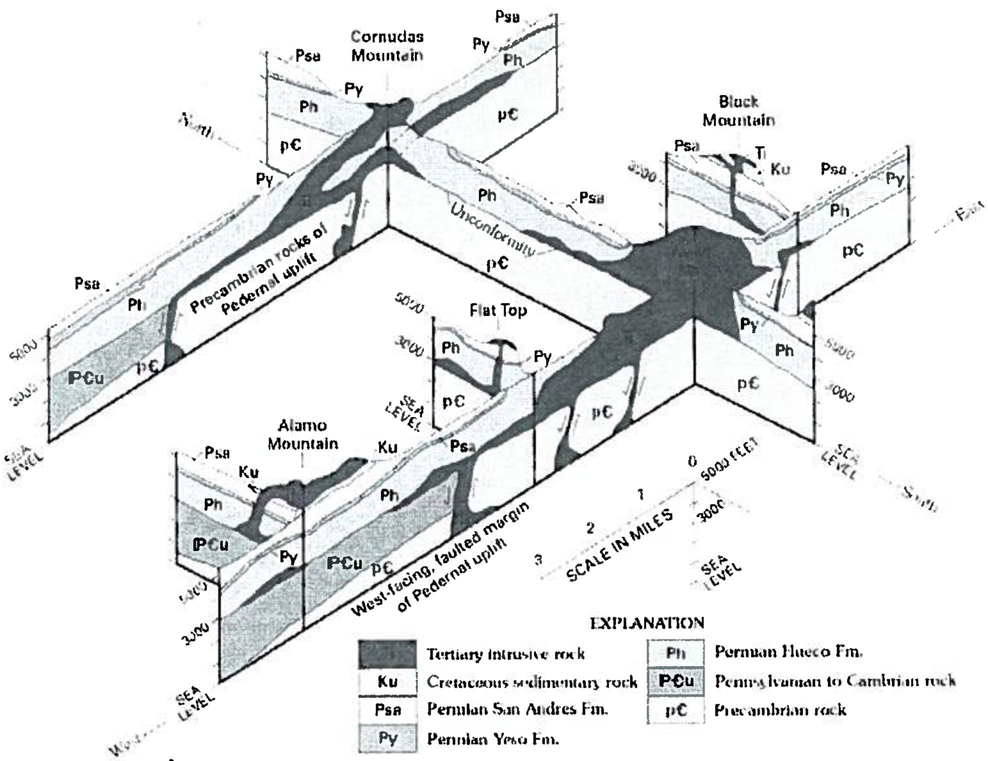


Figure 16. Fence Diagram of Cornudas Mountain Area
(from O'Neill and others, 1998)

It is expected that, although fractured, the intrusives represent a zone of lower hydraulic conductivity than the surrounding limestone. This expectation is based on a comparison of reported specific capacities in the area (e.g. Parizek, 1979, pp. 5 and 8, and Figure 2) and reported specific capacities of wells completed in Tertiary igneous aquifers located elsewhere in the Trans-Pecos region (Far West Texas Regional Planning Group, 2001, pg. 27).

The agricultural area in and around Dell City is on a broad alluvial outwash plain that is underlain by the limestone that occurs on the surface of the Diablo Plateau (Ashworth, 1995). The alluvium is not considered a significant aquifer due to its limited areal extent and limited thickness. Most of the wells in the area are completed in the underlying limestone.

To the east of the agricultural area, the Salt Basin graben is filled with alluvial sediments that are reported to be between 800 and 2,000 ft thick (Gates and others, 1980, pg. 13). East of the Salt Basin graben, the area is dominated by the shelf margin and reef deposits of Guadalupe age (Capitan and Goat Seep).

Uliana (2001, pp. 154 and 155) provided an overview of the Capitan Reef Aquifer, which included maps of the Capitan Reef Aquifer from two different sources that have slightly different western boundaries.

4.2 Structure

Regional faulting associated with the basin and range tectonics divides the study area into three parts: the Diablo Plateau on the west, the Salt Basin graben in the central portion, and the upland shelf and reef limestones along the margins of the Guadalupe and Delaware Mountains. The faulting down-dropped the Salt Basin and fault movement has continued to present (Sharp, 2001, pg. 44 and Goetz, 1977, pg. 23). Reed (1965, pp 11-12) concluded that, based on an analysis of groundwater elevation gradients, the faulting in the area defines the boundary between the Salt Basin graben and upland limestone area, has "enhanced the development of porosity and permeability" of the limestone, and has not acted as a barrier to movement into the Salt Basin.

Flexures and fracture systems in the carbonate units play a major role in the hydrogeology of the region (Sharp, 2001, pg. 44 to 45), and are presented in Figure 17.

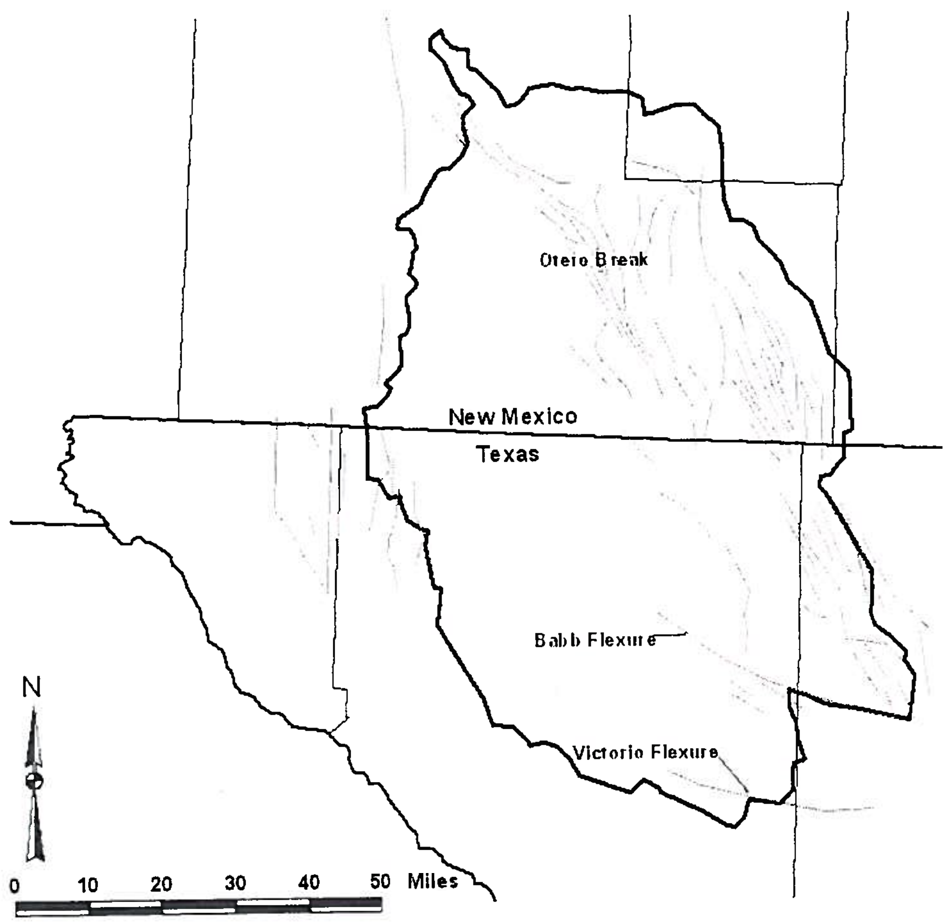


Figure 17. Generalized Location of Faults and Flexures

Mayer (1995, pg. 138) demonstrated the importance of the group of faults known as the Otero Break in the enhancement of groundwater movement of water from the Sacramento Mountains to the Dell City area. Sharp (1989, pg. 27) noted the high hydraulic conductivity in limestones in the vicinity of the Babb Flexure. Sharp (1989, pg. 27) cited Nielson and Sharp (1985) regarding the proximity of groundwater divides and the Babb and Victorio flexures and suggested that

> *Tectonic movement and resultant trends of sedimentation created permeability barriers, in addition to controlling the locations of the surface drainage systems and the alluvial fans that serve as the prime recharge sites.*

4.3 Water Levels and Regional Groundwater Flow

Groundwater elevation data were obtained from the Texas Water Development Board (TWDB) website for the Texas portion of the study area. Groundwater elevation data for the New Mexico portion of the study area were obtained from Hibbs and others (1997), and from the New Mexico State Engineer website. Locations for all wells that have at least one data point are shown in Figure 18.

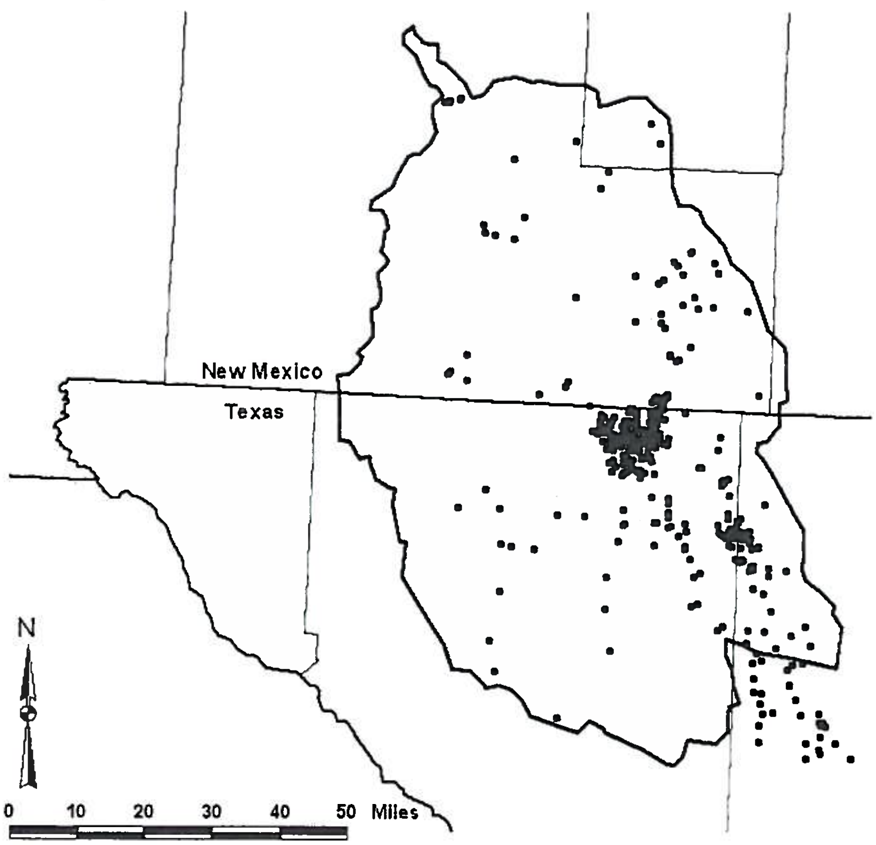


Figure 18. Well Locations in the Dell City Area

Several wells in the Dell City area exhibit similar trends in groundwater elevations changes over time, and exhibit little difference in groundwater elevation. The locations of selected wells are shown in Figure 19. Hydrographs of these wells are shown in Figures 20 to 24. The groundwater level response in the hydrographs suggest, as Bjorklund (1957, pg.12) concluded, that the aquifer is highly permeable and that the "solution channels are interconnected and belong to a common hydraulic system". This also suggests that the equivalent porous medium assumption used by Mayer (1995, pg 117) is valid, at least on a regional scale.

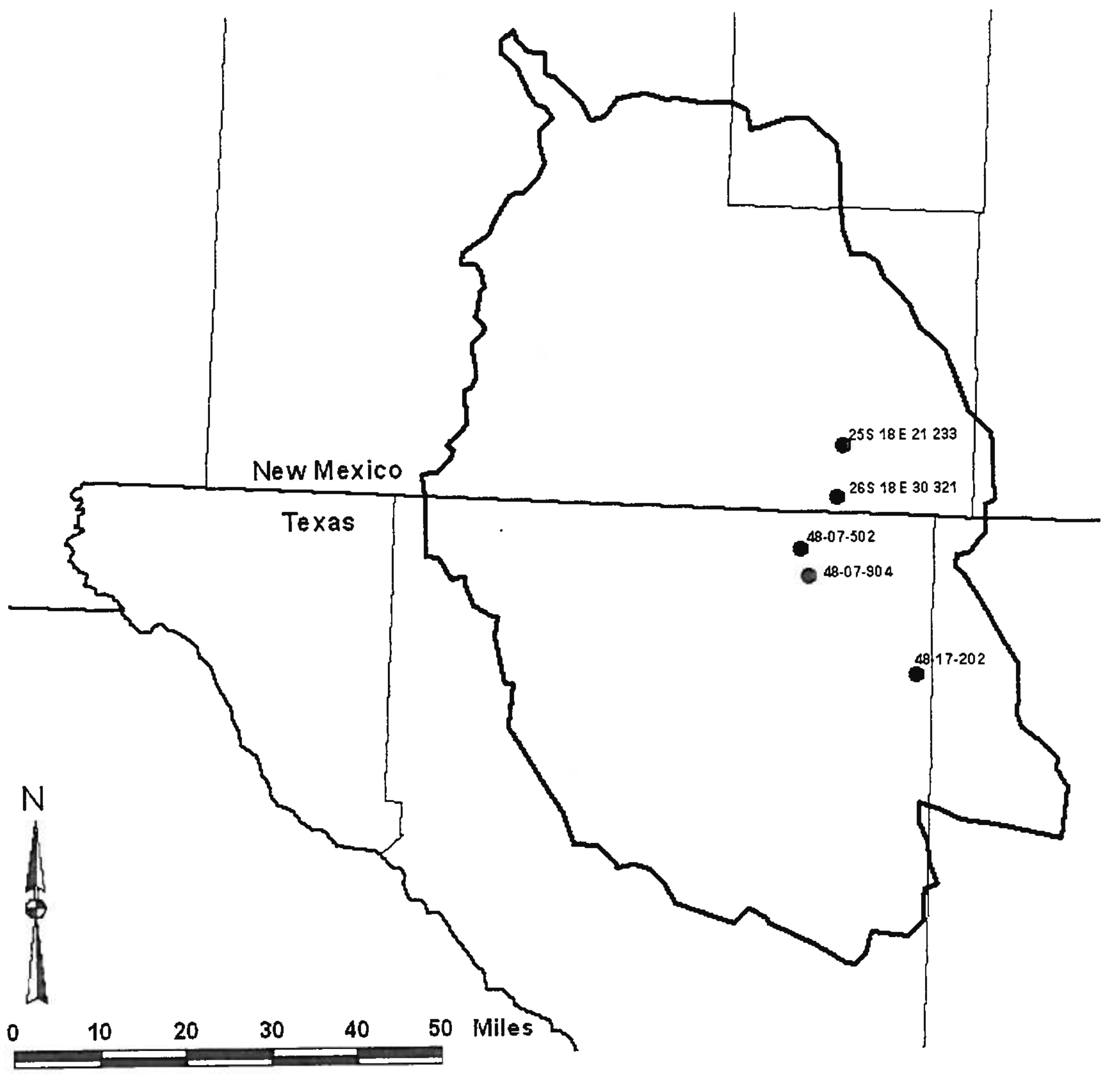


Figure 19. Location of Selected Wells

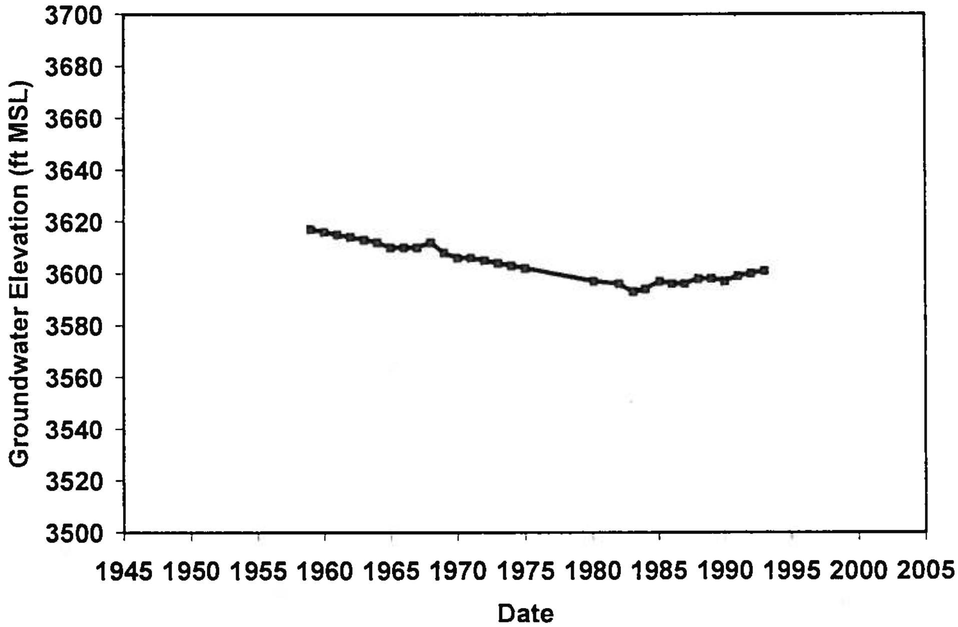


Figure 20. Hydrograph of Well 25S 18E 21 233

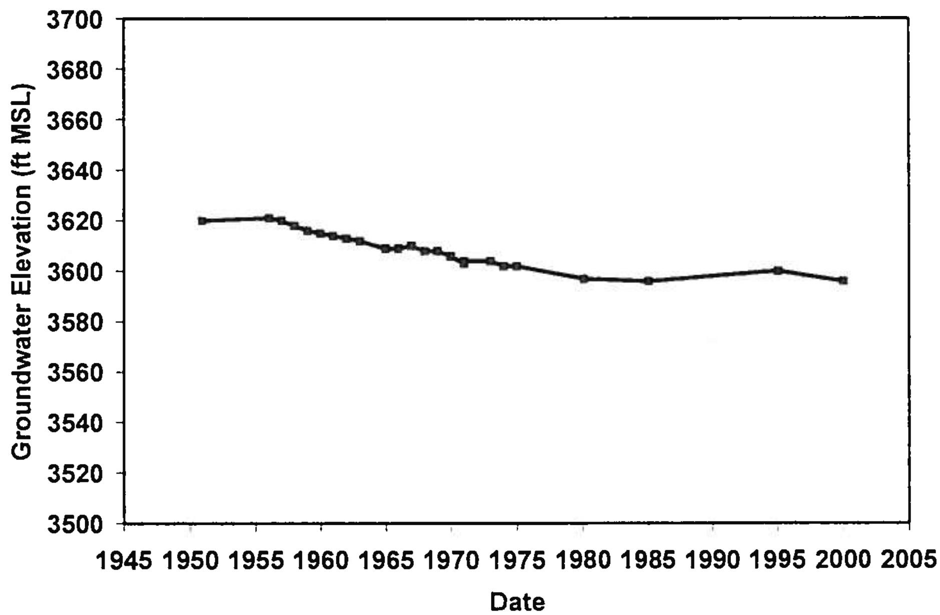


Figure 21. Hydrograph of Well 26S 18E 30 321

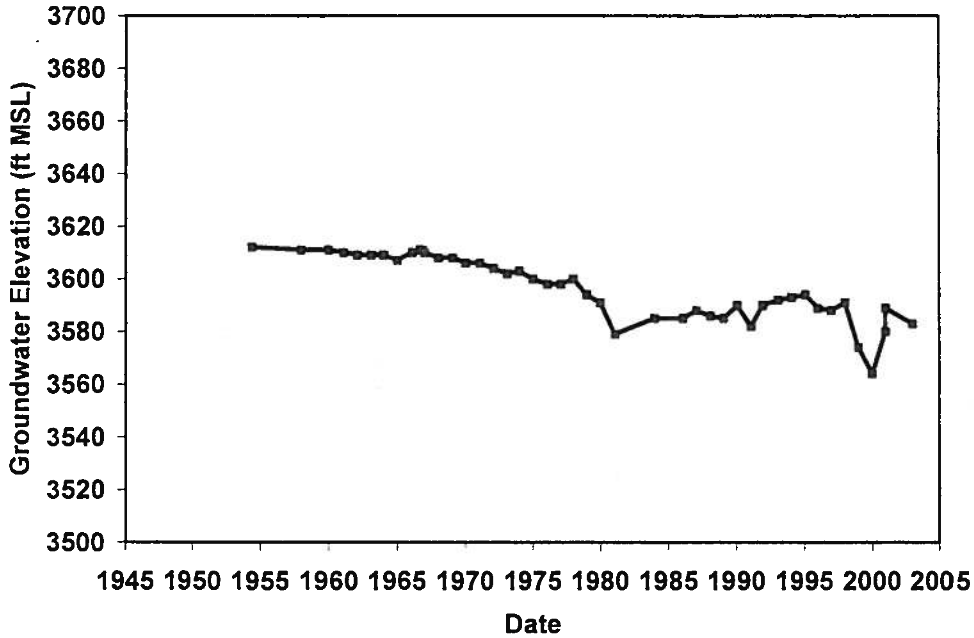


Figure 22. Hydrograph of Well 48-17-202

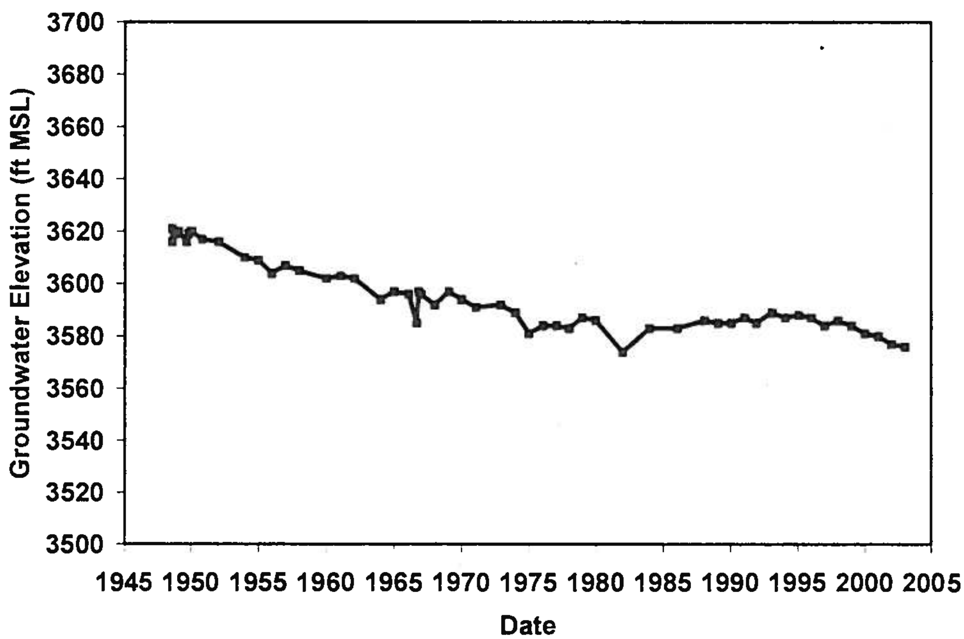


Figure 23. Hydrograph of Well 48-07-502

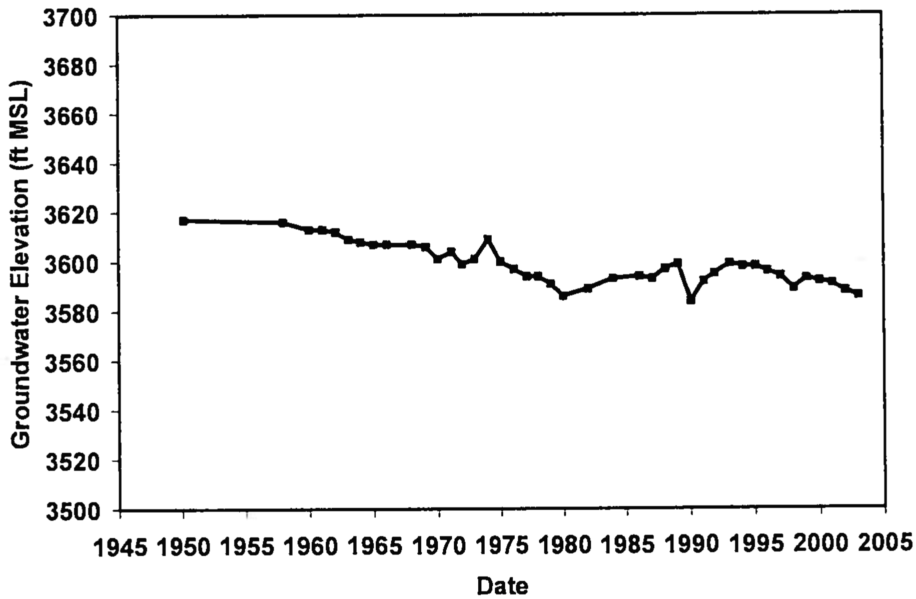


Figure 24. Hydrograph of Well 48-07-904

Note that the hydrographs generally depict declining groundwater levels after 1948 at the beginning of high irrigation pumping. Groundwater elevations tended to stabilize after 1980. Several contributing factors can be used to explain this observation: 1) groundwater pumping decreased after 1980, 2) precipitation (and by extension recharge) in the area was higher after 1980 than before 1980, and 3) the cone of depression expanded and "captured" natural outflow (most likely evapotranspiration). One of the reasons to develop a groundwater model is to investigate these factors and understand their relative roles in explaining the observed decline then stabilization of groundwater elevations.

Contour maps of groundwater elevation (previously presented as Figures 10 and 15) presented by Hibbs and others (1979), and Huff and Chace (2006) show that groundwater in the Dell City area is derived from the north (from the Sacramento Mountains towards Dell City), and from the west (from the Diablo Plateau towards Dell City). The playa appears to act as a sink to groundwater flow prior to the start of pumping in 1948. Since pumping began, it appears that groundwater elevation declines have induced some flow from the playa to the west, into the Dell City area. This is evidenced by decreased groundwater elevations in the Dell City area and the degradation of groundwater quality (Ashworth, 1995).

4.4 Recharge

Table 8 summarizes previous estimates of recharge of the area. Note that in Bjorklund (1957), Ashworth (1995) and Blair (2002b), the estimated recharge was based on an analysis of pumping and groundwater elevation response. The stated assumption made in these three recharge estimates is that if groundwater elevations are stable over a period of time, then total recharge equals pumping. In reality, stable groundwater elevations over a period of relatively constant pumping is evidence that total inflow (natural recharge plus induced recharge) equals total outflow (pumping plus natural outflow). Ashworth (1995) also noted the impact of irrigation return flow on observed changes in groundwater quality.

Table 8. Summary of Recharge Estimates

Source	Estimate	Area	Remarks
Scalapino (1950, pg. 6)	N/A	Dell City Area	Recognized that most recharge is from infiltration of Sacramento River flows
Bjorklund (1957, pg.15)	< 100,000 AF/yr	Crow Flats and Dell City Areas	Based on evaluation of pumping and groundwater elevation response from 1948 to 1955
Reed (1965, pg. 18)	15,400 AF/yr	Diablo Farms Area of the Capitan and Goat Seep	Darcian estimate, limited to upper 700 feet of aquifer
Ashworth (1995, pg 13)	90,000 to 100,000 AF/yr	Bone Spring-Victorio Peak Aquifer	Includes both lateral inflow and irrigation return flow. Based on analysis of groundwater pumping and groundwater elevations response
Mayer (1995, pg 126)	88,366 to 100,527 AF/yr	Otero Mesa, Diablo Plateau, Crow Flats, Salt Basin	Included 58,370 AF/yr of "distributed recharge" and between 29,996 to 42,156 irrigation return flow
Blair (2002b, pg.13)	160,000 to 200,000 AF/yr	Bone Spring-Victorio Peak Aquifer	Estimates by John Ashworth based on reinterpretation of Ashworth (1995). Range is based on assumed range of duties. Estimates include return flow component.
Finch (2002)	54,943 AF/yr	Otero Mesa, Diablo Plateau, Crow Flats, Salt Basin	Based on steady-state model simulation
Eastoe and Hibbs (2005)	N/A	Dell City, Diablo Plateau, Sacramento Mountains	Isotopic sampling suggests that significant recharge in the Texas portion of Dell City is from the Diablo Plateau, west of Dell City

Note that the "estimate" of recharge by Eastoe and Hibbs (2005) does not deal with quantity, but rather with the suggestion that significant groundwater flow in the Texas portion of the Dell City area is from the Diablo Plateau to the west of Dell City. This is based on the similarity in isotopic signature of groundwater in the Diablo Plateau and the Texas portion of Dell City. In contrast, groundwater in the New Mexico portion of the Dell City area (Crow Flats in some reports and the Salt Basin in other reports) has a similar isotopic signature with Sacramento Mountain groundwater and is different than the isotopic signature of groundwater in the Texas portion of Dell City.

When groundwater elevations are stable at some level of pumping, total inflows to the system and total outflows from the system (including pumping) are matched. The cone of depression that has formed in the Dell City area defines the domain of this "system". Under this condition, the inflow to the system includes 1) recharge from precipitation on land overlying the domain, 2) irrigation return flow, 3) naturally occurring lateral inflow to the area, and 4) induced lateral inflow of groundwater that has responded to the change in gradient caused by pumping. When groundwater elevations are stable, the sum of these four inflow components is equal to the pumping plus the natural outflow from the system. In this area, natural outflow from the system is evapotranspiration from the playa.

It is possible that, within a fairly broad range of pumping, groundwater elevations could remain stable. Assuming groundwater elevations are currently "stable", if pumping were reduced 10 percent from present amounts, the induced inflow would be reduced and groundwater elevations would stabilize at a higher level than present after an adjustment period. If pumping were increased 10 percent, it is likely that induced inflow would be increased and groundwater elevations would stabilize at a lower level than present after an adjustment period. If pumping were increased to the point that no additional inflow could be induced, groundwater elevations would decline without stabilization. This is an undesirable situation as storage would be depleted and groundwater mining would be occurring.

The hydrographs of groundwater elevations presented in the previous section depict an initial decline in groundwater elevations after the development of irrigated agriculture in the late 1940s. The hydrographs also show stabilization after 15 to 20 years of pumping. Based on these hydrographs, it appears that a new dynamic equilibrium has been established. Based on this observation, it is concluded that inflow has been induced into the area, thus effectively increasing the "recharge" to the Dell City area. It is also likely that natural discharge to the playa and/or any subsurface outflow has been reduced as a result. The combination of induced inflow and decreased natural outflow is the "capture".

Mayer's (1995) investigation was a good starting point to address the potentially complex relationships between pumping and capture. However, the objectives of his study focused on evaluating the role of fracture orientation and anisotropy on the flow system, and simulated the system under steady state conditions. This steady-state simulation cannot be used to evaluate the groundwater budget changes associated with pumping in the Dell City area.

Mayer's (1995, pp 125 to 132) estimates of distributed recharge were based on a combination of the Maxey-Eakin approach in higher elevation areas and rates estimated from soil chloride data in lower elevation areas. Mayer (1995, pg. 129 to 130) utilized the same distribution of recharge factors as a basin in eastern Nevada. The Maxey-Eakin method is an empirical technique developed for a specific basin in eastern Nevada, where precipitation is dominant in the winter. Precipitation in the higher elevation areas of the study area is highest in the summer months. Although the basic approach is correct (Stone and others, 2001), it is unlikely that strict application of the parameters that were empirically developed for a basin in Nevada can be used without modification in the Sacramento Mountains.

As discussed previously, the recharge estimate used by Mayer (1995) was simply an input to the model, and transmissivity values were adjusted during calibration of the model. It was noted by Mayer (1995, pg. 122) that the resulting transmissivity values were an order of magnitude less than the highest values reported in the literature. Given the modeling approach taken, it is likely that if the transmissivity values were adjusted higher to be consistent with the highest end of the literature values and recharge was adjusted upward commensurately, an equally good calibration would be achieved. Conversely, if transmissivity values were lowered, an equally good calibration could be achieved with lower estimates of recharge. Based on an analysis of past recharge estimates, it is apparent that recharge is known only within very broad ranges. The basic approach of Maxey-Eakin (i.e. higher recharge rates at higher elevations) is appropriate. However, it is also clear that the estimate of recharge is highly correlated with estimates of pumping and with estimates of transmissivity.

Recharge from irrigation return flow has been estimated as 30% of total pumping (Blair, 2002a) based on current irrigation practices (i.e. sprinklers). This recharge, and return flows during periods when flood irrigation dominated, has contributed to increased total dissolved solids (i.e. a degradation of groundwater quality) according to the analysis of Ashworth (1995).

4.5 Rivers, Streams, Springs, and Lakes

Surface flows in the study area are limited to ephemeral drainages that flow after precipitation events. Bjorklund (1957, pg 14) discussed the role of these ephemeral streams in recharging the aquifer system. Based on observations of residents, runoff from the higher elevations infiltrates into the canyon floors and bajadas. Water that reaches the valley floor often drains into the various sinkholes. According to local residents, many floods in the various arroyos are dissipated before reaching the playa area. Livingston Associates and John Shomaker Associates (2002, pg. 6-21) reported that average annual flow in the Sacramento River at a gauging station at the "upper part of the watershed" from 1984 to 1989 was 2,173 AF/yr.

Springs in the area reported in the literature connected to the aquifer system include Crow Spring. Bjorklund (1957, pg 14 and 15) noted that the groundwater pumping caused declines in groundwater elevations sufficient to dry up Crow Spring that was noted as a flowing about 3 gallons per minute by Scalapino (1950, pp 20-21). Other seeps and springs in the area are located along the margin of the playa where groundwater intersects the land surface and becomes part of the overall natural discharge of the system. As development has increased since the late 1940s, this discharge has been reduced. Other springs include Alamo Spring in the Cornudas Mountains and Carrizo Spring in the Sacramento Mountains, which is one of the primary water sources for community of Timberon.

4.6 Hydraulic Properties

Hydraulic properties of the aquifer include hydraulic conductivity, transmissivity and storativity. Hydraulic conductivity was originally defined as an empirical parameter in describing flow through porous media, and is analogous to permeability. It can be defined as the flow rate of water through a cross section of the aquifer of unit area under a unit hydraulic gradient. Transmissivity is defined as hydraulic conductivity multiplied by the aquifer thickness. Storativity is defined as the volume of water that an aquifer releases from storage per unit surface area of aquifer per unit decline in the component of hydraulic head normal to that surface (Freeze and Cherry, 1979, pg. 60).

Hydraulic conductivity typically varies spatially and directionally in a groundwater flow system. If hydraulic conductivity differs with direction, the aquifer is termed anisotropic. Anisotropy is distinct from heterogeneity, which means that hydraulic conductivity varies spatially due to some hydrogeologic factor (e.g. grain size, rock type, or fracture density). Huntoon (1995, pg 351 and 352) points out that karst aquifers are highly anisotropic, and that it is inappropriate to model karst aquifers as extremely heterogeneous as an approximation for what is truly anisotropic. Geologic evidence points to the conclusion that the study area can be considered a karstic system. Therefore, the development of this groundwater flow model included treating hydraulic conductivity and transmissivity as anisotropic parameters.

Table 9 summarizes specific capacity tests (which can be used to estimate transmissivity) from Scalapino (1950), Bjorklund (1957), and White and others (1980). Table 10 summarizes empirical estimates of transmissivity using methods presented by Gates and others (1980), and Mace (2001, Figure 7).

Note that wells in Scalapino (1950) were all assumed completed in limestone aquifers. This is based on data in Scalapino (1950) that the casing of the well is considerably less than the total depth of the well, suggesting open-hole completions in limestone. Bjorklund (1957) presented data that specify which tests are from wells completed in limestone and which tests are from wells completed in alluvium. White and others (1980) presented data that are primarily located in the Capitan and Goat Seep formations on the east side of the study area. Brown and Caldwell (2001) completed aquifer tests on the Layton Farm and O'Ban Farm. Estimated transmissivities ranged from 41,200 to 87,200 ft^2/day on the Layton Farm and ranged from 336,500 to 448,600 ft^2/day on the O'Ban Farm (Brown and Caldwell, 2001, pg. 3-3).

Storativity estimates in the literature are sparse. Gates and others (1980, pg.18) opined that the specific yield of the Capitan Limestone is probably large in places where the limestone is cavernous, but overall the specific yield of the formation is probably 5 percent or less (storativity of 0.05).

Table 9. Summary of Specific Capacity Tests

Well ID	Source	Well Depth (ft)	Pumping Rate (gpm)	Specific Capacity		
				gpm/ft	ft^2/day	m^2/day
47-17-204	White and others (1980)	890	790	7	1,251	116
47-17-206	White and others (1980)	750	470	8	1,482	138
26.18.33.111	Bjorklund (1957)	425	400	8	1,540	143
47-17-602	White and others (1980)	200	410	9	1,636	152
47-17-208	White and others (1980)	1,686	2,000	12	2,310	215
26.18.33.133	Bjorklund (1957)	435	1,200	13	2,567	238
67	Scalapino (1950)	250	620	15	2,911	270
47-17-218	White and others (1980)	350	1,300	16	3,080	286
47-17-904	White and others (1980)	400	1,500	16	3,080	286
47-18-706	White and others (1980)	400	1,500	16	3,080	286
30	Scalapino (1950)	280	350	18	3,369	313
66	Scalapino (1950)	250	700	19	3,642	338
47-09-801	White and others (1980)	412	2,400	25	4,763	442
29	Scalapino (1950)	304	1,500	33	6,417	596
47-17-203	White and others (1980)	500	2,450	38	7,316	680
47-17-202	White and others (1980)	250	1,000	43	8,278	769
47-17-317	White and others (1980)	600	2,000	58	11,166	1,037
21	Scalapino (1950)	250	1,250	60	11,459	1,065
34	Scalapino (1950)	255	1,300	65	12,513	1,162
26.18.32.122	Bjorklund (1957)	300	3,000	67	12,834	1,192
41	Scalapino (1950)	230	1,800	90	17,326	1,610
17	Scalapino (1950)	300	1,500	100	19,251	1,788
81	Scalapino (1950)	154	2,900	104	19,939	1,852
10	Scalapino (1950)	237	1,500	115	22,213	2,064
47-09-207	White and others (1980)	1,240	2,450	136	26,203	2,434
24	Scalapino (1950)	200	1,100	138	26,471	2,459
47-17-321	White and others (1980)	1,120	1,600	200	38,503	3,577
26.18.30.122	Bjorklund (1957)	386	2,000	250	48,128	4,471
111	Scalapino (1950)	231	2,000	286	55,004	5,110
42	Scalapino (1950)	220	1,800	360	69,305	6,439
26.18.113	Bjorklund (1957)	394	3,620	362	69,690	6,474
47-09-207	White and others (1980)	1,240	1,500	375	72,193	6,707
26.18.29.113	Bjorklund (1957)	333	2,180	545	104,920	9,747
26.18.29.113a	Bjorklund (1957)	298	2,610	653	125,615	11,670
24.19.18.144	Bjorklund (1957)	480	3,500	1167	224,599	20,866

Table 10. Estimates of Transmissivity Based on Specific Capacity Tests

Well ID	Transmissivity Estimate (ft^2/day) Method 1	Method 2	Method 3	Method 4	Method 5	Method 6	Method 7	Method 8	Average	Minimum	Maximum
47-17-204	1,300	2,145	1,642	1,526	1,391	1,952	1,370	887	1,527	887	2,145
47-17-206	1,540	2,541	1,884	1,783	1,671	2,332	1,643	1,048	1,805	1,048	2,541
26.18.33.111	1,600	2,640	1,943	1,846	1,741	2,428	1,711	1,088	1,875	1,088	2,640
47-17-602	1,700	2,805	2,041	1,952	1,859	2,588	1,826	1,154	1,991	1,154	2,805
47-17-208	2,400	3,960	2,699	2,678	2,698	3,716	2,641	1,618	2,801	1,618	3,960
26.18.33.133	2,667	4,400	2,939	2,950	3,023	4,151	2,956	1,795	3,110	1,795	4,400
67	3,024	4,990	3,255	3,310	3,463	4,738	3,382	2,030	3,524	2,030	4,990
47-17-218	3,200	5,280	3,407	3,486	3,681	5,027	3,593	2,146	3,727	2,146	5,280
47-17-904	3,200	5,280	3,407	3,486	3,681	5,027	3,593	2,146	3,727	2,146	5,280
47-18-706	3,200	5,280	3,407	3,486	3,681	5,027	3,593	2,146	3,727	2,146	5,280
30	3,500	5,775	3,663	3,785	4,055	5,523	3,954	2,343	4,075	2,343	5,775
66	3,784	6,243	3,902	4,065	4,411	5,994	4,298	2,529	4,403	2,529	6,243
47-09-801	4,948	8,165	4,850	5,200	5,894	7,945	5,728	3,289	5,752	3,289	8,165
29	6,667	11,000	6,174	6,834	8,132	10,865	7,879	4,405	7,744	4,405	11,000
47-17-203	7,600	12,540	6,865	7,706	9,368	12,467	9,065	5,008	8,827	5,008	12,540
47-17-202	8,600	14,190	7,588	8,631	10,706	14,195	10,347	5,653	9,989	5,653	14,195
47-17-317	11,600	19,140	9,670	11,357	14,790	19,435	14,252	7,580	13,478	7,580	19,435
21	11,905	19,643	9,875	11,630	15,210	19,972	14,653	7,775	13,833	7,775	19,972
34	13,000	21,450	10,605	12,607	16,727	21,905	16,100	8,475	15,109	8,475	21,905
26.18.32.122	13,333	22,000	10,824	12,903	17,191	22,495	16,542	8,688	15,497	8,688	22,495
41	18,000	29,700	13,803	16,991	23,771	30,828	22,806	11,659	20,945	11,659	30,828
17	20,000	33,000	15,033	18,715	26,636	34,434	25,527	12,927	23,284	12,927	34,434
81	20,714	34,179	15,466	19,327	27,665	35,727	26,504	13,380	24,120	13,380	35,727

Table 10. Estimates of Transmissivity Based on Specific Capacity Tests (continued)

Well ID	Transmissivity Estimate (ft^2/day)										
	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6	Method 7	Method 8	Average	Minimum	Maximum
10	23,077	38,077	16,880	21,339	31,088	40,017	29,751	14,873	26,888	14,873	40,017
47-09-207	27,222	44,917	19,297	24,829	37,160	47,597	35,503	17,487	31,752	17,487	47,597
24	27,500	45,375	19,456	25,061	37,570	48,107	35,891	17,662	32,078	17,662	48,107
47-17-321	40,000	66,000	26,355	35,337	56,310	71,297	53,593	25,499	46,799	25,499	71,297
26.18.30.122	50,000	82,500	31,577	43,360	71,655	90,121	68,046	31,731	58,624	31,577	90,121
111	57,143	94,286	35,183	49,009	82,771	103,686	78,497	36,168	67,093	35,183	103,686
42	72,000	118,800	42,427	60,578	106,238	132,162	100,519	45,361	84,761	42,427	132,162
26.18.113	72,400	119,460	42,617	60,886	106,876	132,934	101,117	45,608	85,237	42,617	132,934
47-09-207	75,000	123,750	43,853	62,888	111,027	137,951	105,007	47,212	88,336	43,853	137,951
26.18.29.113	109,000	179,850	59,363	88,605	166,258	204,271	156,657	68,104	129,013	59,363	204,271
26.18.29.113a	130,500	215,325	68,682	104,509	201,939	246,774	189,935	81,245	154,864	68,682	246,774
24.19.18.144	233,333	385,000	109,966	178,063	378,248	454,239	353,702	143,586	279,517	109,966	454,239

Method 1	Multiply specific capacity in gpm/ft by 200 (Gates and others, 1980, pg. 18)
Method 2	Multiply specific capacity in gpm/ft by 330 (Gates and others, 1980, pg. 18)
Method 3	$T = 3.24(SC)^{0.81}$ Mace (2001, Figure 7a -- carbonate aquifer in northwestern Ohio)
Method 4	$T = 1.81(SC)^{0.917}$ Mace (2001, Figure 7d -- fractured carbonate aquifer)
Method 5	$T = 0.76(SC)^{1.08}$ Mace (2001, Figure 7e -- Edwards Aquifer, Texas)
Method 6	$T = 1.23(SC)^{1.05}$ Mace (2001, Figure 7f -- carbonate aquifer, Florida)
Method 7	$T = 0.785(SC)^{1.07}$ Mace (2001, Figure 7g -- fractured carbonate aquifer)
Method 8	$T = 0.78(SC)^{0.98}$ Mace (2001, Figure 7k -- Edward-Trinity Aquifer (limestone), Texas)
Note	All methods presented by Mace require specific capacity in m^2/day and transmissivity is estimated in m^2/day

4.7 Playa Discharge

Discharge from the study area is by evaporation from the playa and from groundwater pumping. Prior to development in the late 1940s, all discharge was from evaporation from the playa (Bjorklund, 1957, pg. 15). A small amount was discharged at Crow Springs (Scalapino, 1950, pp 20 to 21). By 1955, pumping had caused groundwater elevations to decline to the point where discharge to the playa was reduced (Bjorklund, 1955, pg. 15), and flow at Crow Springs had ceased (Bjorklund, 1957, pp 14 and 15). Groundwater elevations along the margins of the playa dropped from about 3,620 in well 48-08-401 in the early 1950s to between 3590 and 3600 in wells 48-08-401 and 48-08-102 in the late 1990s.

Although somewhat ambiguous, Mayer (1995, pg 126, and 132 to 138) appears to have suggested that pre-development playa evaporation was 105,391 AF/yr, and post development playa evaporation is between 7,296 and 19,457 AF/yr. Groeneveld and Baugh (2002) estimated playa discharge through evaporation for eight years from 1984 to 2002. These estimates are presented in Table 11.

Table 11. Groeneveld and Baugh (2002) Estimates of Playa Discharge

Year	Area of Discharge (Ac)	Estimated Discharge (AF/yr)	Average Rate of Discharge (ft/yr)
1984	16,104	38,852	2.41
1985	14,182	40,101	2.83
1988	18,070	44,089	2.44
1989	8,530	19,662	2.31
1992	13,006	26,282	2.02
1998	12,615	25,805	2.05
2001	5,553	12,176	2.19
2002	8,837	12,472	1.41

4.8 Groundwater Pumping

Groundwater pumping has not been metered historically, and there is a wide range of estimates of how much has been pumped. Irrigated acreage and pumping estimates that were previously summarized (not including Groeneveld and Baugh, 2002) are summarized in Table 12. The pumping data include estimates of both total pumping and consumptive pumping. Total pumping represents the total amount of water pumped in a year. Consumptive pumping represents total pumping less the irrigation return flow or "leaching fraction". The leaching fraction is the water that passes through the root zone and infiltrates back to the water table, and is necessary to limit salt build-up in the root zone. Blair (2002a) estimated the leaching fraction to be 30% of total pumping in the

Dell City area. The relatively high leaching requirement is largely due to the high total dissolved solids in the irrigation water.

Note that several years include two estimates of pumping. Ashworth (1995, pg. 5 and Figure 3) presented estimates of acreage and pumping, and were assumed to represent total pumping, a portion of which recharged the aquifer as irrigation return flow. In 2002, John Ashworth presented information to the Hudspeth County Underground Water Conservation District No. 1 that represented a reinterpretation of his previous estimates based on a new assumption that the previous pumping estimates represented consumptive pumping rather than total pumping (reported in Blair, 2002b, pg 13). These reinterpreted estimates are based on assumed application rate of 6.6 AF/acre for flood irrigation. This new interpretation did not include a reevaluation of irrigated acreage estimates.

Blair (2002a) developed an estimate of pumping for the year 2001. This estimate started with the assumption that of the 28,803 acres of farmland listed by the Hudspeth Appraisal District, 27,000 acres were actually irrigated in 2001. Based on metered data from one particular farm (CLM), an average withdrawal rate of 4.0 AF/acre was assumed for the entire District. Multiplying the 4.0 AF/acre by the 27,000 acres yielded a total pumping estimate of 108,000 AF. Blair (2002a) further assumed that the irrigation return flow was 32,400 AF, or 30% of the total pumping for sprinkler irrigation. Subtracting the return flow from the total pumping yields an estimate of the consumptive water use of 75,600 AF.

Subsequent to Blair (2002a and 2000b), Groeneveld and Baugh (2002, pg. 15 and 16) completed an analysis of annual irrigated acreage and consumptive pumping from 1974 to 2002 (except 1978, 1989 and 1993) using satellite imagery. These estimates are summarized in Table 13. Consumptive pumping was estimated using a Blaney-Criddle approach for alfalfa during a normal year, less average annual precipitation (Groeneveld and Baugh, 2002, pg.11). Consumptive pumping was estimated by multiplying irrigated acres by the estimated irrigation requirement of 3.859 ft/yr.

Table 12. Pre-Groeneveld and Baugh (2002) Estimates of Irrigated Acreage and Pumping

Year	Irrigated Acreage	Estimated Pumping (AF/yr)	Source of Estimates	Remarks
1949		18,000	Scalapino (1950)	
1955		100,000	Bjorklund (1957)	
1958	19,000	65,000	Ashworth (1995)	
1960	25,000	100,000	Gates and others (1980)	
1964	29,000	90,000	Ashworth (1995)	See Note
1964	29,000	191,400	Blair (2002b)	Total Pumping
1967		105,000	Gates and others (1980)	
1969	20,000	85,000	Ashworth (1995)	See Note
1969	20,000	132,000	Blair (2002b)	Total Pumping
1972		100,000	Gates and others (1980)	
1974	33,000	130,000	Ashworth (1995)	See Note
1974	33,000	217,800	Blair (2002b)	Total Pumping
1979	39,000	144,000	Ashworth (1995)	See Note
1979	39,000	257,400	Blair (2002b)	Total Pumping
1984	19,000	100,000	Ashworth (1995)	See Note
1984	19,000	125,400	Blair (2002b)	Total Pumping
1989	20,000	95,000	Ashworth (1995)	See Note
1989	20,000	132,000	Blair (2002b)	Total Pumping
2001	27,000	108,000	Blair (2002a)	Total Pumping
2001	27,000	75,600	Blair (2002a)	Consumptive Pumping

Note:
Originally presented as Total Pumping by Ashworth (1995). Subsequent work by Ashworth (in Blair, 2002b, pg 13) suggested that these estimates may represent consumptive pumping

Table 13. Groeneveld and Baugh (2002) Estimates of Irrigated Acreage and Consumptive Pumping

Year	Irrigated Acres	Consumptive Pumping (AF/yr)
1974	29,825	115,093
1975	33,656	129,877
1976	26,410	101,917
1977	32,810	126,615
1978	No data	No data
1979	29,422	113,538
1980	30,930	119,359
1981	22,249	85,860
1982	27,923	107,754
1983	18,509	71,426
1984	16,807	64,859
1985	16,857	65,050
1986	20,333	78,465
1987	17,692	68,274
1988	19,169	73,972
1989	No data	No data
1990	16,873	65,111
1991	16,767	64,704
1992	13,847	53,437
1993	No data	No data
1994	12,585	48,567
1995	16,388	63,239
1996	18,581	71,706
1997	16,149	62,318
1998	19,526	75,349
1999	19,246	74,272
2000	21,651	83,552
2001	21,660	83,584
2002	19,327	74,582

Figure 25 presents a comparison of the irrigated acreage estimates of Groeneveld and Baugh (2002) with those of Ashworth (1995) and Blair (2002a). In the four common years (1974, 1979, 1984, and 2001), the estimates of Groeneveld and Baugh (2002) are lower than those of Ashworth (1995) and Blair (2002a). Recall that Groeneveld and Baugh (2002) estimated irrigated acreage based on Landsat data. The estimates of Ashworth (1995) and Blair (2002a) were based on a review of crop reports, which are reports of irrigated acreage associated with various government farm programs. Irrigated acreage reported in a government crop report did not necessarily receive irrigation water for that particular year. Acreage that is temporarily fallowed is considered "irrigated acreage" in various farm programs. Therefore, it is possible that estimates of Ashworth (1995) and Blair (2002a) included acreage that did not actually receive irrigation water in that particular year.

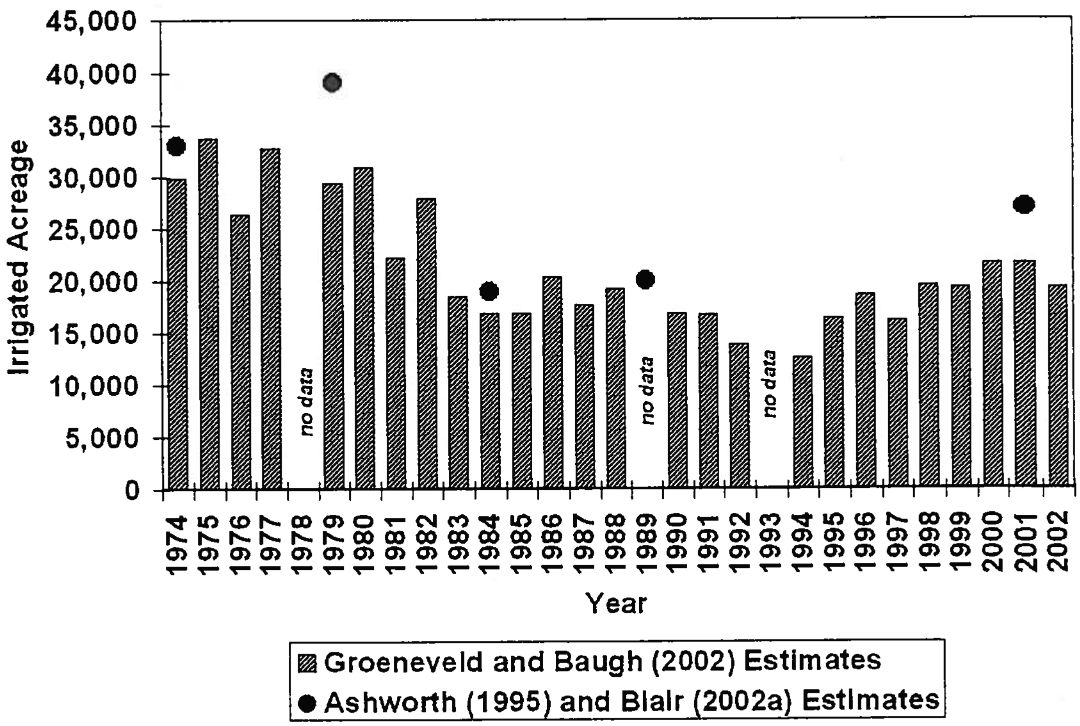


Figure 25. Comparison of Irrigated Acreage Estimates

Table 14 summarizes the comparison of consumptive pumping estimates of Groeneveld and Baugh with those of Ashworth (1995) and Blair (2002a). Recall that Groeneveld and Baugh (2002) estimated consumptive pumping by multiplying irrigated acreage by the estimated irrigation requirement (or duty) of 3.859 ft/yr. Also recall that Ashworth (1995) estimated irrigated acreage and pumping that, at the time, were considered estimates of total pumping. John Ashworth (in Blair, 2002b) reinterpreted the data and suggested that the 1995 estimates were, in fact, consumptive pumping. Finally, recall that Blair (2002a) estimated consumptive pumping an estimate of irrigated acreage and metered pumping data based on data from one farm in the Dell City area.

Table 14. Comparison of Consumptive Pumping Estimates

Year	Groeneveld and Baugh (2002) Estimates			Ashworth (1995) and Blair (2002a) Estimates		
	Irrigated Acres	Consumptive Pumping (AF/yr)	Duty (AF/acre/yr)	Irrigated Acres	Consumptive Pumping (AF/yr)	Duty (AF/acre/yr)
1974	29,825	115,093	3.86	33,000	130,000	3.94
1975	33,656	129,877	3.86	ND	ND	ND
1976	26,410	101,917	3.86	ND	ND	ND
1977	32,810	126,615	3.86	ND	ND	ND
1978	ND	ND	ND	ND	ND	ND
1979	29,422	113,538	3.86	39,000	144,000	3.69
1980	30,930	119,359	3.86	ND	ND	ND
1981	22,249	85,860	3.86	ND	ND	ND
1982	27,923	107,754	3.86	ND	ND	ND
1983	18,509	71,426	3.86	ND	ND	ND
1984	16,807	64,859	3.86	19,000	100,000	5.26
1985	16,857	65,050	3.86	ND	ND	ND
1986	20,333	78,465	3.86	ND	ND	ND
1987	17,692	68,274	3.86	ND	ND	ND
1988	19,169	73,972	3.86	ND	ND	ND
1989	ND	ND	ND	20,000	95,000	4.75
1990	16,873	65,111	3.86	ND	ND	ND
1991	16,767	64,704	3.86	ND	ND	ND
1992	13,847	53,437	3.86	ND	ND	ND
1993	ND	ND	ND	ND	ND	ND
1994	12,585	48,567	3.86	ND	ND	ND
1995	16,388	63,239	3.86	ND	ND	ND
1996	18,581	71,706	3.86	ND	ND	ND
1997	16,149	62,318	3.86	ND	ND	ND
1998	19,526	75,349	3.86	ND	ND	ND
1999	19,246	74,272	3.86	ND	ND	ND
2000	21,651	83,552	3.86	ND	ND	ND
2001	21,660	83,584	3.86	27,000	75,000	2.80
2002	19,327	74,582	3.86	ND	ND	ND

ND = No Data

If the reinterpreted data of Ashworth (1995) truly reflect consumptive pumping, and the Groeneveld and Baugh (2002) assumption regarding the irrigation requirement is correct, the duties should be comparable. Indeed, duty estimates of the Ashworth data range from 3.69 AF/acre/yr (in 1979) to 5.26 AF/acre/yr (in 1984). As noted above, if the Ashworth (1995) estimates of irrigated acreage are too high, the duty estimates would be slightly lower, which would result in even closer agreement with the estimates of Groeneveld and Baugh (2002).

Blair (2002a) estimated a consumptive duty of 2.80 AF/acre/yr for the 2001 irrigation year. This estimate is lower than the other estimates as presented, and may be reflective of an average duty of both irrigated and fallowed acreage in any particular year. From a groundwater management perspective, it is realistic to recognize that not all irrigable land will be irrigated in any particular year. However, care should be exercised when comparing the various estimates to distinguish between actual irrigated acreage and an entire area that has both irrigated and temporarily fallowed land.

Table 15 presents a comparison of estimates of total pumping. Groeneveld and Baugh (2002) estimated irrigated acreage and consumptive pumping. Blair (2002a) estimated a leaching fraction of 30%. The leaching fraction is the amount of water that is pumped, applied as irrigation water, and passes through the root zone back to the water table as a means of managing the salt build-up in the soil. The estimate of total pumping and duty under the Groeneveld and Baugh (2002) column represents adding the 30% leaching fraction estimated by Blair (2002a) to the irrigated acreage estimates and consumptive pumping estimate of Groeneveld and Baugh (2002). With a consumptive duty of 3.86 AF/ac, this yields a total duty estimate of 5.51 AF/ac.

The estimated total pumping of Ashworth (1995) for four years between 1974 and 1989 represent the reinterpreted estimates as found in Blair (2002b). John Ashworth (as found in Blair, 2002b) reinterpreted the 1995 data to possibly represent consumptive pumping, and the actual duty associated with total pumping for flood irrigation is up to 6.60 AF/acre/yr. Blair (2002a) estimated a total duty of 4.00 AF/acre/yr for the 2001 irrigation year.

The total pumping duties of the reinterpreted Ashworth (1995) data, as reported in Blair (2002b), are higher than the duties estimated using the Groeneveld and Baugh (2002) estimates of irrigated acreage and the Blair (2002a) estimate of leaching fraction. The total pumping duty estimate of Blair (2002a) for the 2001 irrigation season is the lowest. As with the consumptive duty estimate comparison, it is possible that some of the difference is due to the difference between the irrigated acreage estimates (Landsat image based vs. crop report based).

Table 15. Comparison of Total Pumping Estimates

Year	Groeneveld and Baugh (2002) Estimates			Ashworth (1995) and Blair (2001) Estimates		
	Irrigated Acres	Total Pumping (AF/yr)	Duty (AF/acre/yr)	Irrigated Acres	Total Pumping (AF/yr)	Duty (AF/acre/yr)
1974	29,825	164,336	5.51	33,000	217,800	6.60
1975	33,656	185,445	5.51	ND	ND	ND
1976	26,410	145,519	5.51	ND	ND	ND
1977	32,810	180,783	5.51	ND	ND	ND
1978	ND	ND	ND	ND	ND	ND
1979	29,422	162,115	5.51	39,000	257,400	6.60
1980	30,930	170,424	5.51	ND	ND	ND
1981	22,249	122,592	5.51	ND	ND	ND
1982	27,923	153,856	5.51	ND	ND	ND
1983	18,509	101,985	5.51	ND	ND	ND
1984	16,807	92,607	5.51	19,000	125,400	6.60
1985	16.857	92,882	5.51	ND	ND	ND
1986	20,333	112,035	5.51	ND	ND	ND
1987	17,692	97,483	5.51	ND	ND	ND
1988	19,169	105,621	5.51	ND	ND	ND
1989	ND	ND	ND	20,000	132,000	6.60
1990	16,873	92,970	5.51	ND	ND	ND
1991	16,767	92,386	5.51	ND	ND	ND
1992	13,847	76,297	5.51	ND	ND	ND
1993	ND	ND	ND	ND	ND	ND
1994	12,585	69,343	5.51	ND	ND	ND
1995	16,388	90,298	5.51	ND	ND	ND
1996	18,581	102,381	5.51	ND	ND	ND
1997	16,149	88,981	5.51	ND	ND	ND
1998	19,526	107,588	5.51	ND	ND	ND
1999	19,246	106,045	5.51	ND	ND	ND
2000	21,651	119,297	5.51	ND	ND	ND
2001	21,660	119,347	5.51	27,000	108,000	4.00
2002	19,327	106,492	5.51	ND	ND	ND

ND = No Data

5.0 CONCEPTUAL MODEL OF GROUNDWATER FLOW

The conceptual model of groundwater flow in an aquifer system represents the foundation of a numerical model. The conceptual model describes the domain of the flow system, groundwater occurrence, groundwater movement, the inflow components and the outflow components. As part of the conceptual model development, areas of uncertainty and limitations are identified and discussed in the context of model calibration.

5.1 Domain of the Flow System

Figure 26 depicts the domain of the flow system. The watershed divide between the Otero Mesa and the Tularosa Valley and the Hueco Mountains bound the study area on the west, and the Guadalupe and Delaware Mountains bound the area on the east. The Sacramento Mountains represent the northern boundary, and also represent the source of most of the recharge to the aquifer system. The southern boundary is south of the groundwater divide associated with the Babb Flexure. Along the southern boundary in the Salt Basin, a constant head boundary is defined in order to simulate the potential effect of movement of the groundwater divide. Based on Hibbs and others (1997), the western boundary includes an outflow under the Hueco Mountains towards the Hueco Bolson.

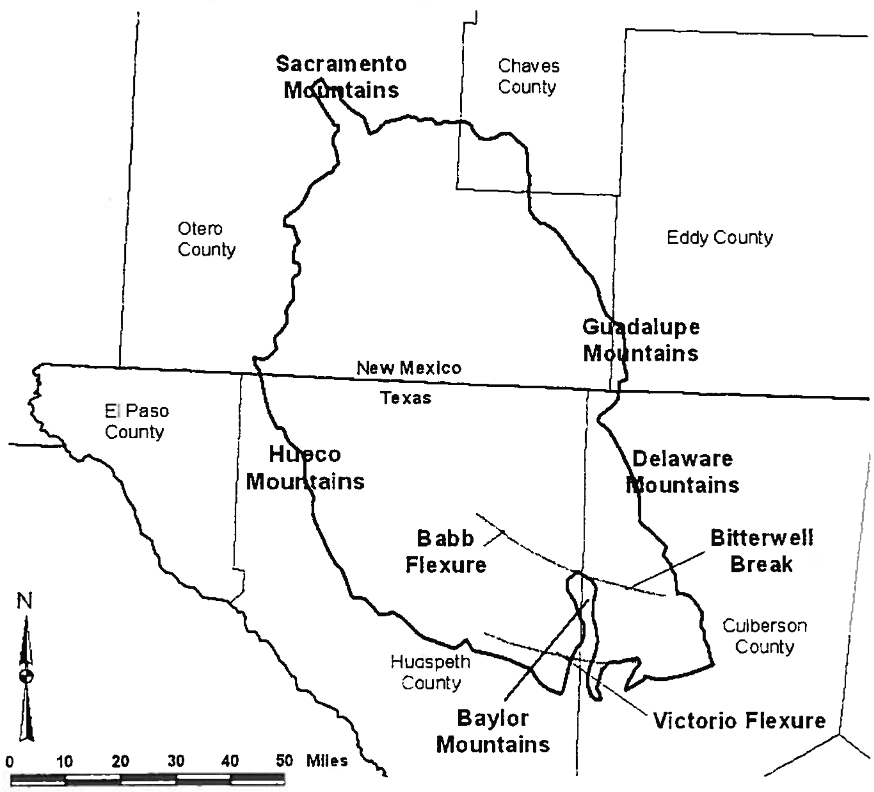


Figure 26. Domain of Groundwater Flow System

The flow system is conceptualized to be a single layer or two-dimensional. Figure 27 depicts the hydrographs of two wells in the Dell City area that are proximate to each other, one shallow (Well 48-07-501, 220 ft deep) and one deep (Well 48-07-505, 910 ft deep). These wells have nearly equivalent groundwater elevations throughout their records, and as such, suggest that there is no vertical gradient.

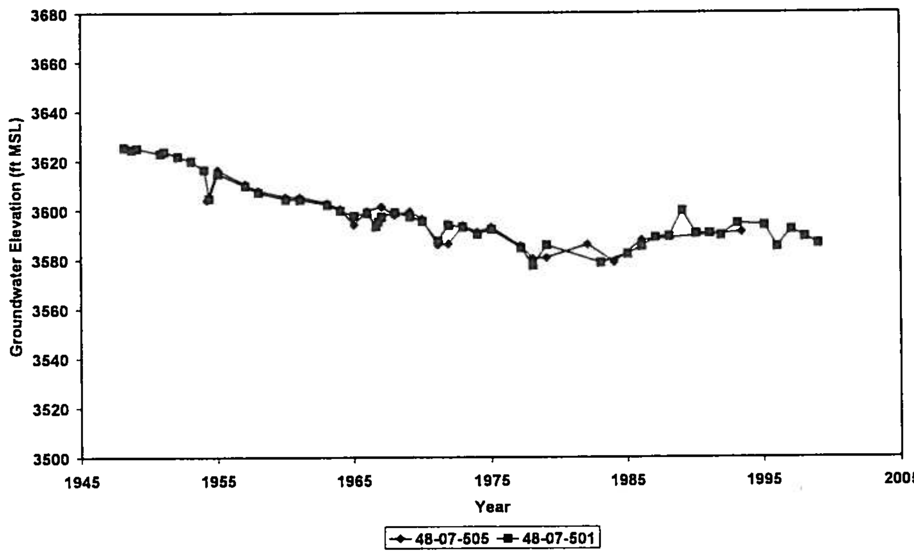


Figure 27. Hydrographs of Paired Wells:
Shallow Well (48-07-501) and Deep Well (48-07-505)

Because the aquifer is relatively thick (on the order of 1000 to 2000 ft), and the variation in groundwater levels is small (less than 50 feet since 1948), transmissivities can be considered reasonably constant. Therefore, aquifer parameters can be described with transmissivity and storativity of the single layer aquifer for purposes of this preliminary modeling effort.

Errors associated with simulating the groundwater flow system as a single layer system with constant transmissivity include: 1) as groundwater elevations decline, saturated thickness decreases, and transmissivity would decrease linearly with drawdown, and 2) if hydraulic conductivity is higher in the shallow portions of the aquifer compared to the deeper portions of the aquifer (as could be suggested from the summary of specific capacity tests previously presented), transmissivity would decrease at a rate faster than linear due to decrease in hydraulic conductivity. Given the relatively small historic changes in groundwater elevations (less than 50 ft in a 1,000 ft saturated thickness) and the preliminary nature of this modeling effort, these errors are considered relatively insignificant.

5.2 Groundwater Occurrence

Groundwater in the study area occurs in three different areas: 1) the upland area associated with the Otero Mesa and Diablo Plateau in the western portion of the study area that consist of fractured carbonate rocks of the Wolfcamp and Leonard series of Permian age, 2) the lower lying area of Quaternary alluvium and playas associated with the Salt Basin and Crow Flats in the central portion of the study area, and 3) the upland area associated with the western slopes of the Guadalupe and Delaware Mountains in the eastern portion of the study area that consist of fractured carbonate rocks of Guadalupe series of Permian age.

The groundwater in the fractured carbonate rocks is conceptualized to occur in the matrix of the rock, in the fractures of the rock, and in the solutionally widened fractures and bedding plane partings, or conduits (White, 1999, pg 18-9). White (1999, pg 18-30 to 18-31) noted:

> *Aquifers with permeability consisting mainly of solutionally widened fractures may be treated with continuum models such as the popular MODFLOW program. The necessary assumption is that the fractures are sufficiently interconnected and closely spaced to justify being treated as a continuum with an average hydraulic conductivity on a regional scale.*

Based on descriptions of the aquifer system described in the literature, previous researchers have considered the aquifer system as being dominated by interconnected conduits. Moreover, the hydrographs of wells in the Dell City area are well correlated with each other. The aquifer system, therefore, is conceptualized as a system that can be treated as a continuum or equivalent porous media. In this conceptualization, it is assumed that an average hydraulic conductivity or transmissivity can be assigned that is a representation of all three components of permeability. This is the same approach as used by Mayer (1995).

The limitation associated with this conceptualization is one of scale, and the associated limitation of using transmissivity estimates developed from pumping tests. Huntoon (1995, pg 353) reported that pumping tests in this type of aquifer can provide hydraulic conductivity estimates that are two orders of magnitude smaller than regional hydraulic conductivity. He further opined that slug, packer and core tests do not yield reliable estimates of hydraulic conductivity or transmissivity for modeling purposes. This conclusion was reached because karst hydraulic conductivities are a function of the volume of the aquifer material being sampled (Sauter, 1993 and Quinlan and others, 1992, as cited in Huntoon, 1995, pg 353). As a result, Huntoon (1995, pg. 353) concluded that the ability to apply a numerical model deteriorates as the scale of the model decreases, and stated that models of karst aquifers of subregional and smaller scales have proven to be highly unreliable.

The limitation associated with the assumption of equivalent porous media is the inability to "scale down" the results, or to use the results for analyses at a subregional scale.

Based on Huntoon's (1995) comments, estimates of hydraulic conductivity or transmissivity that are derived from specific capacity tests and aquifer tests are likely on the low end of true regional hydraulic conductivities and transmissivities. However, it is also likely that the transmissivity estimates derived from specific capacity tests are weighted to "good wells" as low production wells are often abandoned after construction. Therefore, it is possible that the transmissivity estimates previously presented are at the upper end of actual regional transmissivity estimates. During model calibration, adjustments to transmissivity estimates previously presented would need to take these conflicting limitations into account.

5.3 Groundwater Movement

In general, groundwater flows from the surrounding highlands towards the playas, the natural discharge point in the study area. Mayer (1995) concluded that groundwater moves preferentially along fracture alignments from the Sacramento Mountains to the Dell City area. Eastoe and Hibbs (2005) found that isotopic signatures of groundwater suggest that there is also a significant portion of recharge in the Texas portion of the Dell City area from the Diablo Plateau, west of Dell City. The numerical model in this investigation tests these assumptions with the use of three conceptual models: one that emphasizes the structural geology findings of Mayer (1995), one that emphasizes the isotopic signature findings of Eastoe and Hibbs (2005), and one that is a hybrid of the structural geology and isotopic signature models.

At the southern end of the playa within the study area near the Babb Flexure, it is possible that changes in groundwater elevations and gradient could cause a shift in the groundwater divide. Such a shift could reach the model domain boundary, and the additional groundwater could flow into the model domain. A limitation with this approach is that inflow into the model domain from the southern boundary may be overestimated.

5.3.1 Inflow Components

Inflow to the aquifer system is conceptualized to be derived from rainfall that falls within the watershed area. Based on a lack of data to suggest otherwise, it is assumed that there is no flow (even at depth) across the watershed boundaries. In addition, some pumped groundwater is recharged to the aquifer as irrigation return flow. The development of groundwater for irrigation use may have also reversed gradients to the point that groundwater flows into southern end of the study area in the Salt Basin.

For purposes of flow modeling, the irrigation return flow need not be considered. Consequently, all pumping that is simulated would be consumptive or "net" pumping since the irrigation return flow appears to reach the water table within the same year that it was pumped. For the purposes of solute transport modeling, the total pumping would need to be simulated, and the leaching fraction would have to be considered. Groundwater quality changes associated with the irrigation return water is an important aspect of the simulation of groundwater quality.

Similar to Mayer (1995), the amount of precipitation recharge is conceptualized in two categories, rainfall and recharge in higher elevation areas, and rainfall and recharge in lower elevation areas. Mayer (1995, pg. 129 to 130) utilized the Maxey-Eakin method to estimate recharge in the higher elevation areas. The Maxey-Eakin method is an empirical technique developed for a specific basin in eastern Nevada, where precipitation is dominant in the winter. Precipitation in the higher elevation areas of the study area is highest in the summer months. Although the basic approach is correct (Stone and others, 2001), it is unlikely that strict application of the parameters that were empirically developed for a basin in Nevada can be used without modification in the Sacramento Mountains.

Table 16 presents the strict Maxey-Eakin recharge factors, and reasonable minimum and maximum values that should be used in model calibration. Note further that Mayer (1995) applied this method only to areas above elevation 5,496 ft amsl. It is likely that the "Maxey-Eakin" elevation could be higher or lower than 5,496 ft amsl, and should be evaluated during model calibration.

Table 16. Maxey-Eakin Recharge Factors and Alternate Range of Factors

Rainfall (in/yr)	Maxey-Eakin Recharge Rate	Range of Potential Recharge Rates
7.8 to 11.8	3%	1 to 5%
11.8 to 15.0	7%	5 to 11%
15.0 to 19.7	15%	12 to 20%
> 19.7	25%	21 to 30%

For lower elevation areas, the estimated recharge rates are estimated to be between 0.03 and 0.34 in/yr, and are derived from the soil chloride work as cited by Mayer (1995, pg. 128). An appropriate value within this range should be investigated during model calibration.

5.3.2 Outflow Components

Outflow consists of playa evaporation, groundwater pumping, and possibly boundary outflow south of the groundwater divide associated with the Babb Flexure, and west under the Hueco Mountains towards the Hueco Bolson.

Playa evaporation is conceptualized as being at a maximum when groundwater elevations under the playa are at the ground surface. As groundwater pumping has increased, groundwater elevations under the playa have dropped and the evaporation rate has decreased, possibly to zero in some areas. In general, the evaporation rate decreases with increasing groundwater depth until it reaches zero flux at some depth (the "extinction depth"). It is assumed that the extinction depth is about 15 feet, but could range between 5 and 30 feet.

The uncertainty associated with previous pumping estimates has been covered in detail earlier. This uncertainty, coupled with the uncertainty associated with transmissivity estimates and the inability to measure and estimate recharge directly poses a problem in calibrating a groundwater flow model. In essence, a number of non-unique solutions can be developed. These solutions result in estimated groundwater elevations that are reasonably close to historic groundwater elevations. These non-unique solutions further could encompass a wide range of pumping, recharge and transmissivity estimates. For example, a solution can be developed for high pumping, high recharge, and high transmissivity. An essentially equal solution can be obtained with low pumping, low recharge and low transmissivity.

Due to the length of coverage, and the approach taken, the estimates of Groeneveld and Baugh (2002) for irrigated acreage and pumping can be used as a starting point for those particular years of their analysis to begin model development and calibration. Using these estimates will offer some constraint to resulting recharge and transmissivity estimates. All parameters will need refining and checked with the elements of the conceptual model as calibration proceeds.

6.0 MODEL DEVELOPMENT

6.1 Model Overview and Domain

This effort included the development and calibration of three models to further investigate alternative conceptual models of groundwater movement (structural geology, isotope geochemistry, and a hybrid of the structural geology and isotope geochemistry models). Mayer (1995) found strong hydraulic evidence of structural control that suggested that groundwater recharge in the area of the Sacramento Mountains moves towards Dell City. Eastoe and Hibbs (2005) concluded that much of the recharge in the Texas portion of the Dell City area comes from the Diablo Plateau west and south of Dell City based on isotopic signatures of the water.

All three models were developed with MODFLOW-2000 (Harbaugh and others, 2000), the industry standard finite-difference code to simulate groundwater flow developed by the US Geological Survey. The model domain is shown on Figure 28. Note that it roughly corresponds to the watershed except for the northern tip and a portion of the western boundary. All three models have the same domain.

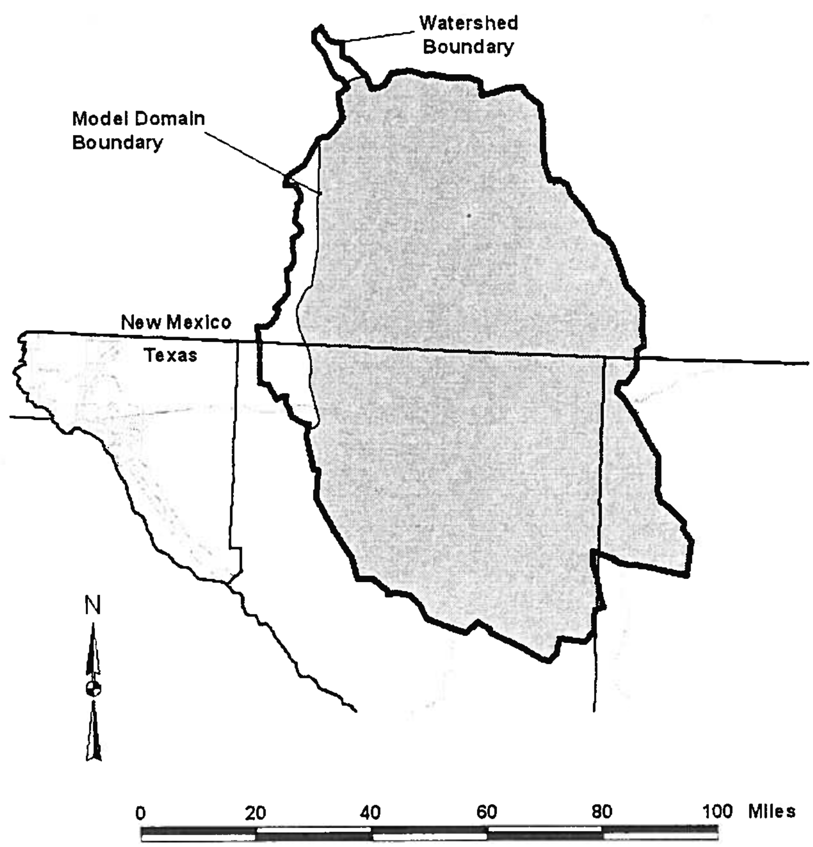


Figure 28. Model Domain Boundary

The coordinate system for the model is based on Texas Central (NAD83) State Plane Coordinates. The model grid offset is 695247.111220065 ft for x and 10389896.2397162 ft for y. Grid rotation is 22 degrees to align with the principal fracture orientation as described by Mayer (1995).

Early versions of the model included the northern tip of the watershed area that extends into the Sacramento Mountains as part of the model domain. However, due to the geometry of this protruding portion of the model, numerical problems were encountered. The final version of the model excluded this portion and replaced it with a general head boundary as described in Section 6.3.7.

The western edge of the model domain does not correspond to the watershed boundary for two reasons: 1) the edge of the model domain corresponds better to the groundwater contours presented by Hibbs and others (1997) that depict westerly flow from the Cornudas Mountains towards the Hueco Bolson west of the watershed boundary (more fully described in Section 6.3.5), and 2) issues associated with the Hueco Ranch that lies west of the model domain and straddles the western watershed boundary (Figure 29).

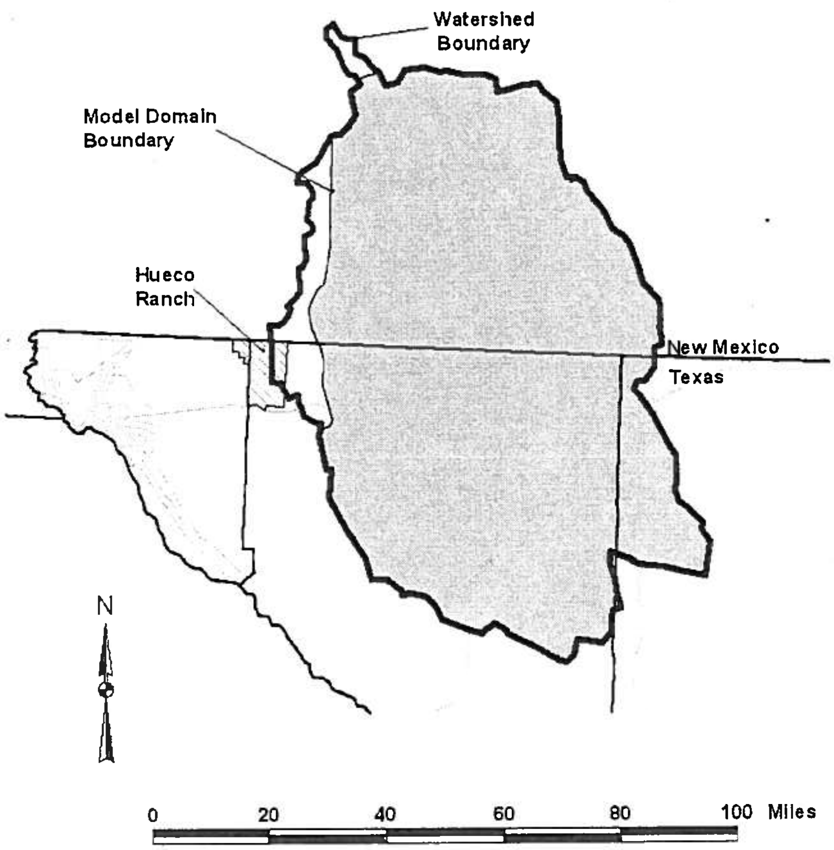


Figure 29. Location of Hueco Ranch

In recent years, the owners of the Hueco Ranch have been marketing the ranch as a potential source of water for the city of El Paso (FWTRPG, 2006, pg 10B-1). If the western model boundary extended to the watershed boundary, a boundary flux would still be necessary, as evidenced by the groundwater elevation contours of Hibbs and others (1997). Also, if the model domain extended to the watershed boundary, there could be a temptation to use model results to draw conclusions relative to groundwater conditions in the area of the Hueco Ranch. The primary objective of this modeling effort is the Dell City area, and use of the model results in the areas near the edge of the model domain may be inappropriate. Therefore, a decision was made to move the western boundary east of the watershed boundary to correspond with a convenient groundwater contour of Hibbs and others (1997), and to prevent any potential misuse or misapplication of the model in the area of the Hueco Ranch.

6.2 Model Packages

Model input files are listed in Table 17. File names for each of the input files for the three models are also listed. Output files are listed in Table 18. File names for each of the output files for the three models are also listed.

Table 17. Summary of Model Input Packages and Filenames

MODFLOW Package	Structural Geology Model Filename	Isotope Geochemistry Model Filename	Hybrid Model Filename
Basic (BAS)	dvs.bas	dvi.bas	dvh.bas
Discretization (DIS)	dvs.dis	dvi.dis	dvh.dis
Layer Property Flow (LPF)	dvs.lpf	dvi.lpf	dvh.lpf
Well (WEL)	dvs.wel	dvi.wel	dvh.wel
Drain (DRN)	dvs.drn	dvi.drn	dvh.drn
Evapotranspiration (EVT)	dvs.evt	dvi.evt	dvh.evt
General Head Boundary (GHB)	dvs.ghb	dvi.ghb	dvh.ghb
Recharge (RCH)	dvs.rch	dvi.rch	dvh.rch
Horizontal Flow Barrier (HFB6)	dvs.hfb	dvi.hfb	dvh.hfb
Constant Head Boundary (CHD)	dvs.chd	dvi.chd	dvh.chd
Output Control (OC)	dvs.oc	dvi.oc	dvh.oc
Geometric Multigrid Solver (GMG)	dvs.gmg	dvi.gmg	dvh.gmg
Initial Heads	odv8.hds	odv8.hds	odv8.hds

Table 18. Summary of Model Output Filenames

Output File	Structural Geology Model Filename	Isotope Geochemistry Model Filename	Hybrid Model Filename
Global Output	dvs.glo	dvi.glo	dvh.glo
List Output	dvs.lst	dvi.lst	dvh.lst
Cell-by-Cell Flow Output	dvs.cbb	dvi.cbb	dvh.cbb
Head Output	dvs.hds	dvi.hds	dvh.hds
Drawdown Output	dvs.ddn	dvi.ddn	dvh.ddn

Each of the MODFLOW packages is discussed below. For each package, the calibrated parameter values are presented. Details of the calibration results are discussed in the next section.

6.2.1 Basic (BAS) Package

The Basic Package specifies the status of each cell (active or inactive), the assigned head for inactive cells (999), and specification of starting heads. Starting heads for the simulation are found in file *odv8.hds*, as shown in Table 17.

6.2.2 Discretization (DIS) Package

The Discretization Package specifies the spatial and temporal discretization of the model. The model contains one layer, 281 rows and 171 columns. Cell size is 2,000 ft by 2,000 ft. The model grid in the area of HCUWCD is presented in Figure 30.

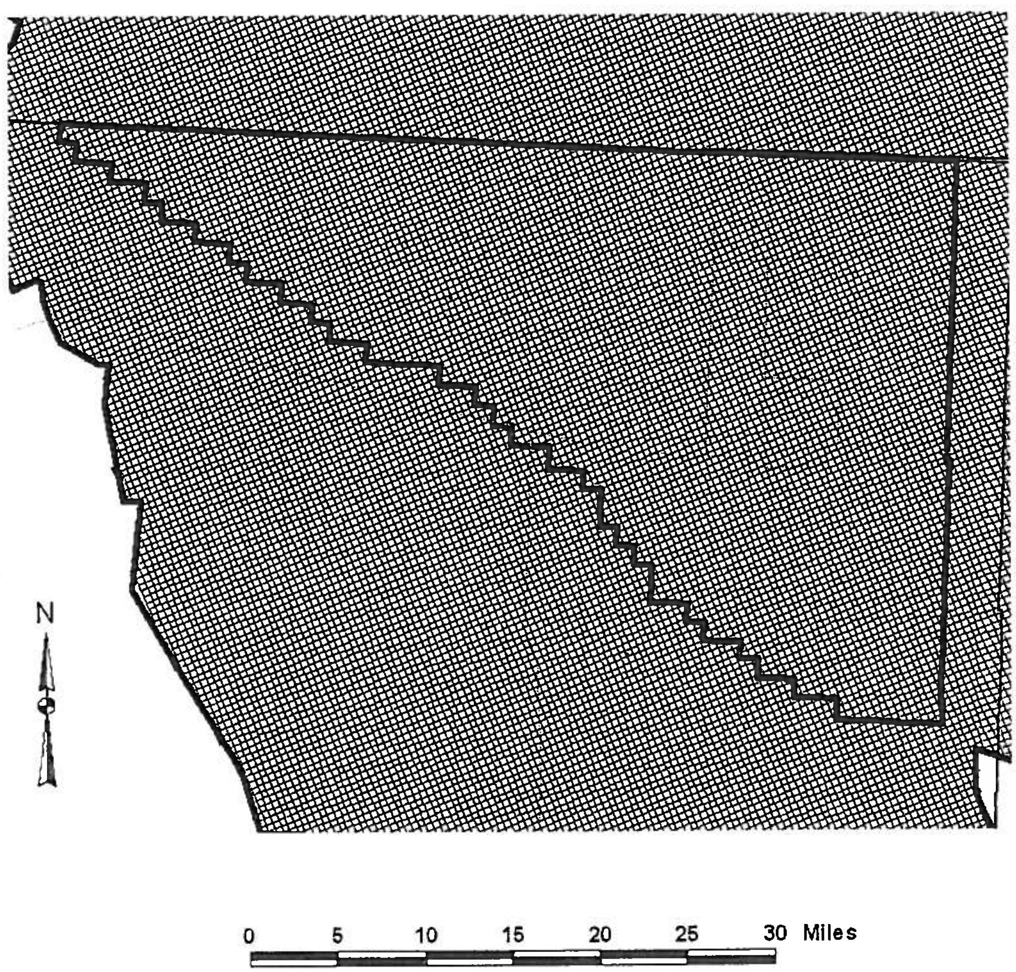


Figure 30. Model Grid in the HCUWCD Area

The time unit for the model is days, and the distance unit for the model is feet. The DIS file also contains the land surface elevation for each cell, and the bottom of the model domain, specified as 1,000 feet below the land surface elevation.

The DIS file defines 56 stress periods defined for the calibration simulation. The first stress period is specified as steady state. This represents the predevelopment period (prior to 1948). The next 55 stress periods are transient, each with a length of 365 days (1 year). These stress periods represent the years 1948 to 2002.

6.3.3 Layer-Property Flow (LPF) Package

The Layer-Property Flow Package specifies the hydraulic conductivity (in both the x and y direction) of each cell in the model domain, and the storativity of the model domain. For all three models, LAYTYP is set to zero (confined, or constant transmissivity) and LAYAVG is set to zero (interblock transmissivity is based on a harmonic mean). CHANI is set to -1, which means that horizontal anisotropy is assigned on a cell-by-cell basis. Hydraulic conductivity is read and multiplied by the assumed aquifer thickness (1,000 ft) to estimate aquifer transmissivity.

In order to facilitate calibration of the three models, the LPF file was written using a pre-processor program (*lpf.exe*) written in FORTRAN. In summary, the *lpf.exe* pre-processor reads a file of aquifer parameter zone numbers and a two database files, one for hydraulic conductivity (*kdb.dat*) and one for specific storage (*sdb.dat*), and writes an output file that can be read by MODFLOW-2000.

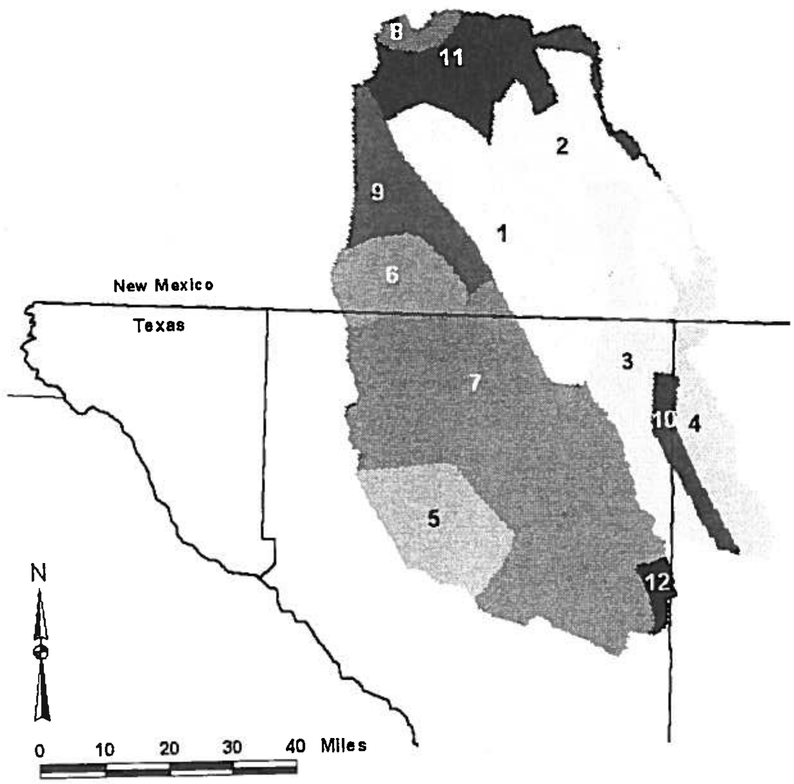
The hydraulic conductivity file contains estimates for hydraulic conductivity in the x, y and z directions. The hydraulic conductivity in the x direction is used for the MODFLOW-2000 variable HK (hydraulic conductivity in the x-direction). The hydraulic conductivity in the y direction is used in the pre-processor to calculate the MODFLOW-2000 variable HANI (ratio of hydraulic conductivity along columns to hydraulic conductivity along rows). Although the hydraulic conductivity database contains a value for vertical hydraulic conductivity and the MODFLOW-2000 input file requires specification of the vertical hydraulic conductivity, these values have no meaning since this is a one-layer model. Similar to hydraulic conductivity, the program uses the same zonation file and the specific storage database to write specific storage estimates for each cell.

The zonation of hydraulic conductivity and specific storage differ in the three models in order to implement the three conceptual models. Hydraulic conductivity and specific storage zones for the three models are shown in Figures 31 to 33. The zones are based on a combination of geology and elevation. The calibrated estimates of hydraulic conductivity and specific storage for each of the models are shown on each zonation figure. Transmissivity and storativity estimates are also provided based on the model assumptions of 1,000 ft aquifer thickness.

The structural geology model (Figure 31) includes 12 zones. Zone 1 represents the Otero Break as described by Mayer (1995). Zone 2 is the higher elevation area east of the Otero Break. Zone 3 is the low lying area associated with the playa (Salt Flat). Zone 4 is the upland area on the slope of the Delaware Mountains, east of the Capitan Reef. Zone 5 covers the Cretaceous rocks in the southwest portion of the study area. Zone 6 covers the upland area of the Cornudas Mountains. Zone 7 is the Diablo Plateau south and east of Dell City. Zone 8 is the highest elevation area of the model in the Sacramento Mountains. Zone 9 is the higher elevation area west of the Otero Break in New Mexico. Zone 10 is the Capitan Reef. Zone 11 is a transition area south of the highest elevations of the Sacramento Mountains and north of the Otero Break. Zone 12 is a small area associated with the Sierra Diablo.

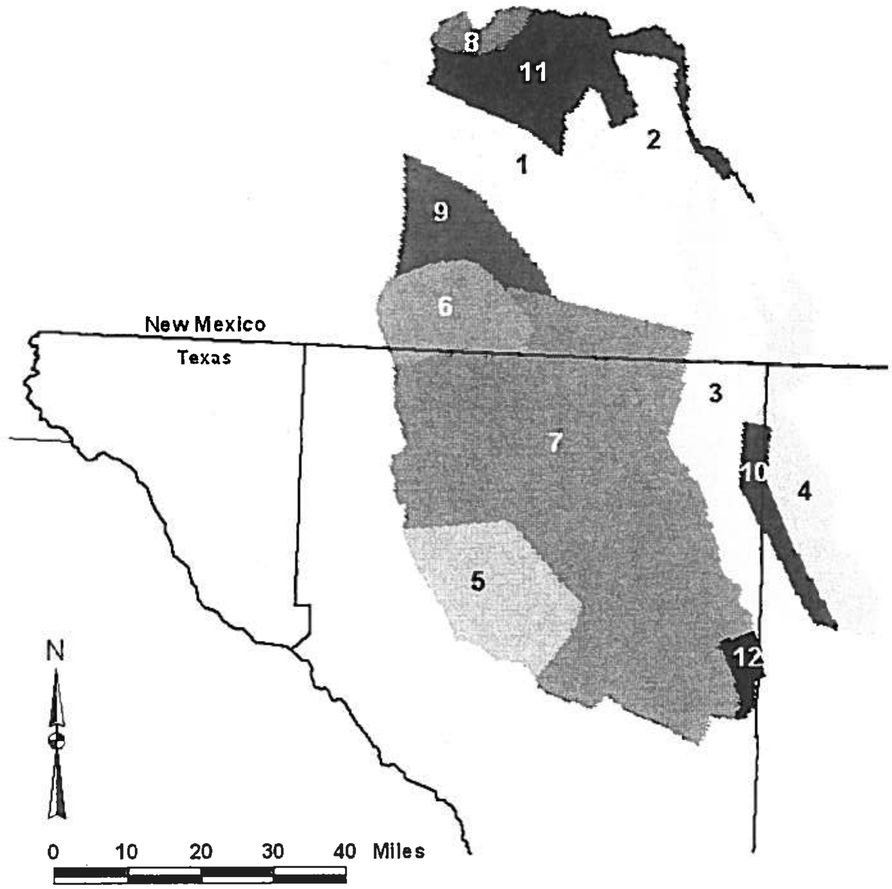
The isotope geochemistry model (Figure 32) includes 12 zones. Zone 1 represents the Permian rocks north of Dell City in New Mexico. Zone 2 is the higher elevation area east of the Otero Break. Zone 3 is the low lying area associated with the playa (Salt Flat). Zone 4 is the upland area on the slope of the Delaware Mountains, east of the Capitan Reef. Zone 5 covers the Cretaceous rocks in the southwest portion of the study area. Zone 6 covers the upland area of the Cornudas Mountains. Zone 7 is the Permian rocks of the Diablo Plateau in Texas and includes Dell City in order to facilitate recharge from the Diablo Plateau to Dell City as suggested by Eastoe and Hibbs (2005). Zone 8 is the highest elevation area of the model in the Sacramento Mountains. Zone 9 is a transition zone between the Cornudas Mountains and Zone 1. Zone 10 is the Capitan Reef. Zone 11 is a transition area south of the highest elevations of the Sacramento Mountains and north of the Otero Break. Zone 12 is a small area associated with the Sierra Diablo.

The hybrid model (Figure 33) includes 12 zones. Zone 1 represents the Permian rocks north of Dell City in New Mexico. Zone 2 is the higher elevation area east of the Otero Break. Zone 3 is the low lying area associated with the playa (Salt Flat). Zone 4 is the upland area on the slope of the Delaware Mountains, east of the Capitan Reef. Zone 5 covers the Cretaceous rocks in the southwest portion of the study area. Zone 6 covers the upland area of the Cornudas Mountains. Zone 7 is the Permian rocks of the Diablo Plateau in Texas, excluding Dell City. Zone 8 is the highest elevation area of the model in the Sacramento Mountains. Zone 9 is the area around Dell City. The isolation of Dell City was a means of testing the assumptions of Mayer (1995) and Eastoe and Hibbs (2005). Through model calibration, the intent was to test the relative contribution of Sacramento Mountain recharge and Diablo Plateau recharge. Zone 10 is the Capitan Reef. Zone 11 is a transition area south of the highest elevations of the Sacramento Mountains and north of the Otero Break. Zone 12 is a small area associated with the Sierra Diablo.



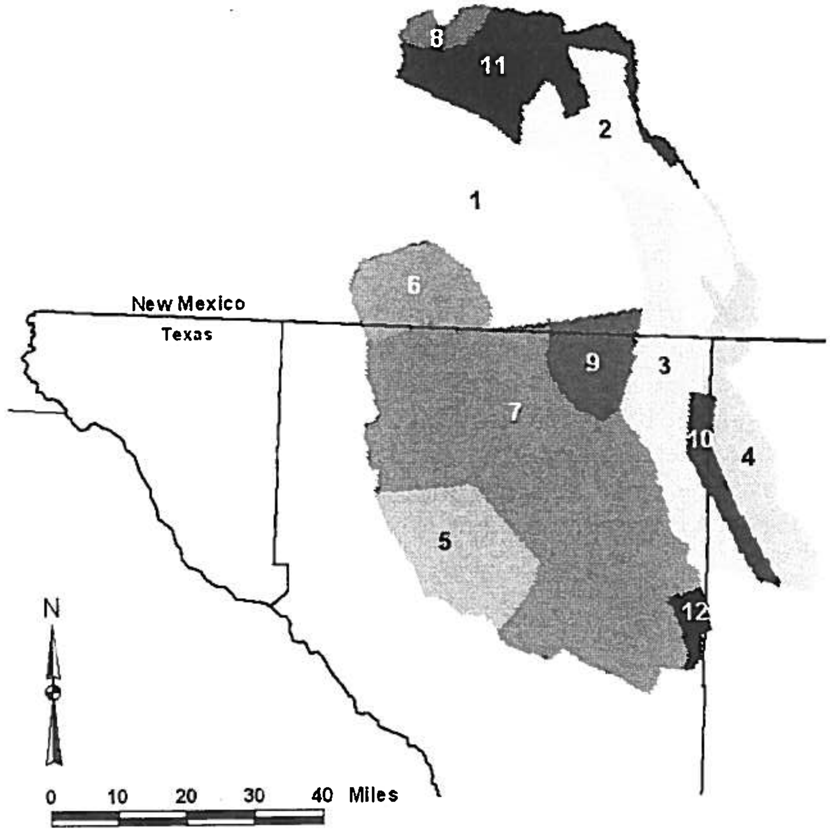
Zone	Area (mi²)	Hydraulic Conductivity (ft/day)		Specific Storage (day⁻¹)	Transmissivity (ft²/day)		Storativity (dimensionless)
		x-direction	y-direction		x-direction	y-direction	
1	540	98.4	179	1.14E-04	98,445	178,545	1.14E-01
2	597	2.01	0.48	1.86E-06	2,007	485	1.86E-03
3	424	49.7	176	2.00E-04	49,745	176,292	2.00E-01
4	309	14.3	5.31	3.56E-07	14,340	5,308	3.56E-04
5	316	0.11	0.45	7.96E-06	113	449	7.96E-03
6	225	2.39E-03	4.17E-03	1.81E-05	2.39	4.17	1.81E-02
7	1,505	10.7	1.00	5.23E-05	10,737	1,000	5.23E-02
8	55	100	146	1.57E-04	100,000	145,932	1.57E-01
9	273	1.00E-03	1.00E-03	3.26E-07	1.00	1.00	3.26E-04
10	96	19.8	40.0	2.70E-06	19,787	39,966	2.70E-03
11	392	4.95	1.01	1.00E-07	4,945	1,015	1.00E-04
12	41	5.48	0.02	1.06E-05	5,479	19.1	1.06E-02

Figure 31. Aquifer Hydraulic Conductivity and Storativity Zonation – Structural Geology Model



Zone	Area (mi^2)	Hydraulic Conductivity (ft/day)		Specific Storage (day^{-1})	Transmissivity (ft^2/day)		Storativity (dimensionless)
		x-direction	y-direction		x-direction	y-direction	
1	598	1.00	98.2	1.00E-07	1,000	98,153	1.00E-04
2	424	1.31	0.43	4.50E-06	1,312	428	4.50E-03
3	419	31.0	17.7	2.00E-04	30,963	17,683	2.00E-01
4	309	100	8.86	2.00E-04	100,000	8,862	2.00E-01
5	316	0.11	1.69	7.28E-06	108	1,690	7.28E-03
6	225	2.42E-03	3.80E-03	2.00E-04	2.42	3.80	2.00E-01
7	1,726	50.0	87.6	2.00E-04	50,000	87,590	2.00E-01
8	55	100	200	2.00E-04	100,000	200,000	2.00E-01
9	198	0.04	2.66	1.00E-07	38.4	2,661	1.00E-04
10	96	6.60	1.00	3.84E-07	6,603	1,000	3.84E-04
11	365	2.16	0.44	1.00E-07	2,162	440	1.00E-04
12	41	0.03	9.86	5.37E-06	26.9	9,860	5.37E-03

Figure 32. Aquifer Hydraulic Conductivity and Storativity Zonation – Isotope Geochemistry Model



Zone	Area (mi^2)	Hydraulic Conductivity (ft/day)		Specific Storage (day^{-1})	Transmissivity (ft^2/day)		Storativity (dimensionless)
		x-direction	y-direction		x-direction	y-direction	
1	903	1.00	46.7	1.00E-07	1,000	46,682	1.00E-04
2	424	1.09	0.48	4.13E-06	1,089	479	4.13E-03
3	419	8.67	75.3	2.00E-04	8,675	75,275	2.00E-01
4	309	24.2	4.63	2.40E-07	24,174	4,630	2.40E-04
5	316	0.11	1.66	7.25E-06	109	1,663	7.25E-03
6	220	3.02E-03	5.10E-03	6.36E-05	3.02	5.10	6.36E-02
7	1,456	50.00	1.00	2.00E-04	50,000	1,000	2.00E-01
8	55	100.00	200.00	2.00E-04	100,000	200,000	2.00E-01
9	167	200.00	193.23	2.00E-04	200,000	193,231	2.00E-01
10	96	1.81	34.8	2.00E-04	1,807	34,817	2.00E-01
11	365	2.53	0.38	1.00E-07	2,526	380	1.00E-04
12	41	1.15	0.02	3.66E-06	1,153	24.8	3.66E-03

Figure 33. Aquifer Hydraulic Conductivity and Storativity Zonation – Hybrid Model

Note that Zones 4, 5, 8, 10, and 12 are the same in all three models. Zones 1, 7 and 9 are the zones that are most different in the three conceptual models. Note that the other zones (2, 3, 6, and 11) are essentially the same in each of the models, and slight changes are due to changes in Zones 1, 7 and 9.

One of the outcomes of the calibration is the relatively high hydraulic conductivity and transmissivity in Zone 8. This is the small area at the northern end of the model domain and represents the inflow from the watershed area of the Sacramento River and inflow from Penasco Basin. This high value could be indicative of a highly fractured aquifer due to the uplift of the Sacramento Mountains. The high values could also be the result of the need for high inflows into the area from the Penasco Basin. Finch (2002) estimated a boundary inflow from Penasco Basin of about 8,000 AF/yr. Most likely, the high values can be explained by a combination of the two factors. Since the primary objective of the model is the area around Dell City, and this northern area of the model in the area of the Sacramento Mountains represents recharge to the Dell City area, any detailed results (such as parameter estimates) in the Sacramento Mountains area should be interpreted with some degree of caution.

6.3.4 Well (WEL) Package

The Well Package was used to simulate pumping from wells for irrigation. In order to facilitate calibration of the three models, the WEL file was written using a pre-processor program (*pumpaf.exe*) written in FORTRAN. In summary, *pumpaf.exe* reads two files: *irrigcells.dat* and *irrigfactors.dat*, and writes three files: a MODFLOW-2000 input file that is read by the WEL package (*dvs.wel*, *dvi.wel*, or *dvh.wel*, depending on the model), a summary file of cell-by-cell pumping for each stress period (*pumpaf.dat*), and a summary file of pumping in each of the 25 pumping zones for each stress period (*pumpsum.dat*). The 25 zones are shown in Figure 34, and were developed to facilitate model calibration

The file *irrigcells.dat* includes the specification of 929 cells that have been identified as irrigated areas at some time after 1948. The first two columns of the file specify the model row and column. The third column specifies the zone number. The fourth column is zero if the zone is outside of HCUWCD and 1 if it is within the boundaries of HCUWCD. Subsequent columns are annual estimates of irrigated acreage within the cell from 1974 to 2002 based on Groeneveld and Baugh (2002). The final three columns are the average, minimum and maximum irrigated acreage from 1974 to 2002.

The file *irrigfactors.dat* contains estimates of duties and correction factors that were used to modify the estimates of irrigated acreage during model calibration. Annual estimates of pumping in AF/yr were calculated for each cell by multiplying the irrigated acreage by the duty (AF/acre) and the correction factor. For 1974 to 2002, the estimates of irrigated acreage developed by Groeneveld and Baugh (2002) were used as initial estimates. Recall that estimates for the years 1978, 1989, and 1993 were not developed. These years were interpolated from preceding and succeeding years. For 1948 to 1973, the pumping estimates were calibrated based on applying a correction factor to the maximum irrigated acreage for each cell from 1974 to 2002. Annual duties from 1948 to 2002 for consumptive use were specified for areas outside the boundaries of HCUWCD and inside the boundaries of HCUWCD.

Tables 19a through 19d summarize annual pumping estimates for the structural geology model. Table 19a covers Zones 1 to 13 for the years 1948 to 1973. Table 19b covers Zones 14 to 25 for the years 1948 to 1973, and includes annual totals for all irrigation pumping zones. Table 19c covers Zones 1 to 13 for the years 1974 to 2002. Table 19d covers Zones 14 to 25 for the years 1974 to 2002, and includes annual totals for all irrigation pumping zones.

Tables 20a through 20d summarize annual pumping estimates for the isotope geochemistry model. Table 20a covers Zones 1 to 13 for the years 1948 to 1973. Table 20b covers Zones 14 to 25 for the years 1948 to 1973, and includes annual totals for all irrigation pumping zones. Table 20c covers Zones 1 to 13 for the years 1974 to 2002. Table 20d covers Zones 14 to 25 for the years 1974 to 2002, and includes annual totals for all irrigation pumping zones.

Tables 21a through 21d summarize annual pumping estimates for the hybrid model. Table 21a covers Zones 1 to 13 for the years 1948 to 1973. Table 21b covers Zones 14 to 25 for the years 1948 to 1973, and includes annual totals for all irrigation pumping zones. Table 21c covers Zones 1 to 13 for the years 1974 to 2002. Table 21d covers Zones 14 to 25 for the years 1974 to 2002, and includes annual totals for all irrigation pumping zones.

Pumping for each model and for each irrigation pumping zone is summarized graphically in Appendix A.

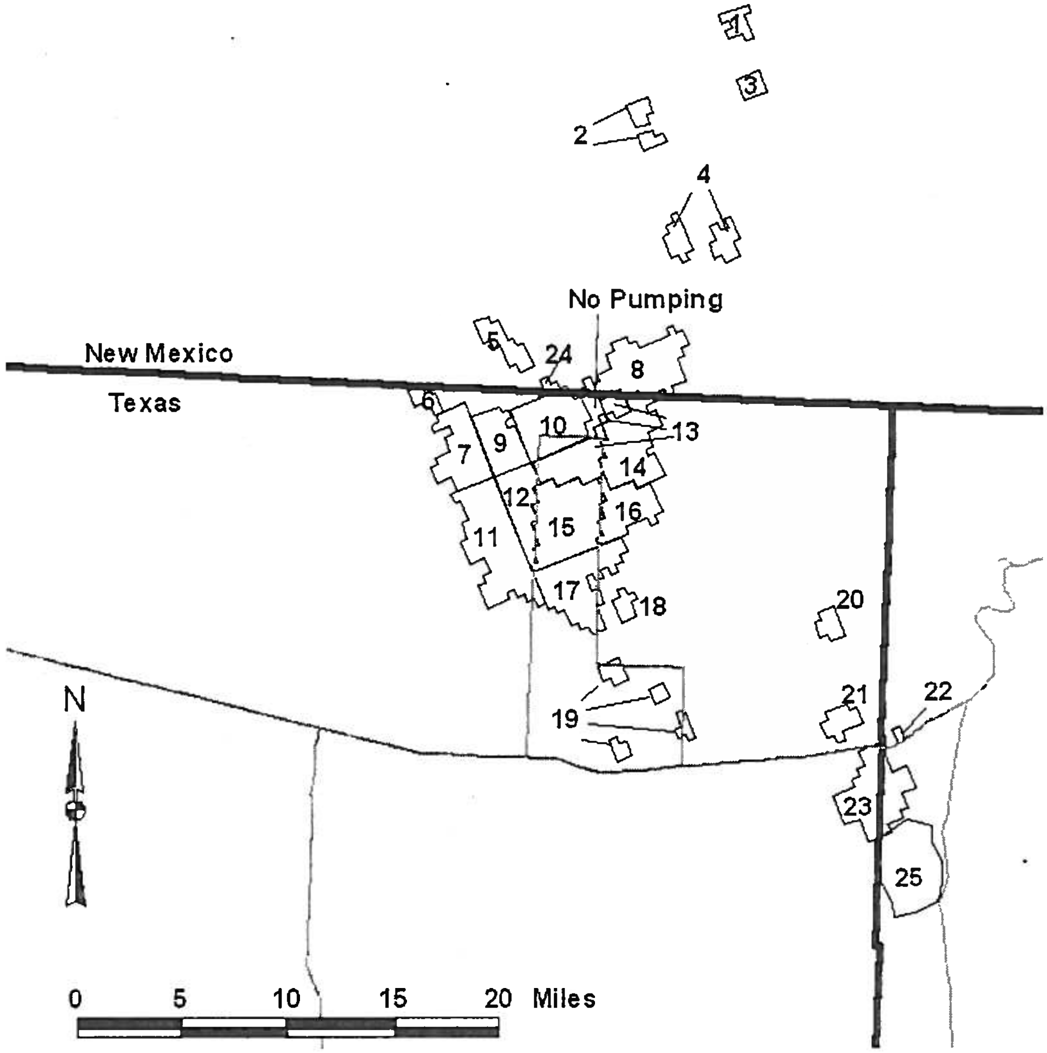


Figure 34. Irrigation Pumping Zones

Table 19a. Pumping Estimates – Structural Geology Model
Zones 1 to 13, Years 1948 to 1973 (Zone Locations in Figure 34)
(all values in AF/yr)

Year	Zone												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1948	0	0	0	0	0	0	0	0	0	0	0	24,797	0
1949	0	0	0	0	0	0	0	0	0	0	0	24,641	0
1950	0	0	0	0	0	0	0	0	0	0	0	24,605	0
1951	0	0	0	0	0	0	0	0	0	18,293	0	13,680	0
1952	0	0	0	0	0	0	0	0	0	12,690	24,871	7,565	0
1953	0	0	0	0	0	0	0	0	18,255	25,598	15,444	4,574	0
1954	0	0	0	0	0	0	11,225	0	13,260	15,538	12,017	9,194	4,185
1955	0	0	0	0	0	0	7,553	0	17,038	19,293	20,567	6,211	8,631
1956	0	0	0	0	0	44	21,305	0	13,147	7,783	11,880	6,853	8,705
1957	0	802	0	0	0	31	11,744	0	14,270	18,088	28,843	11,161	7,949
1958	27	802	0	0	0	23	8,328	0	5,956	18,618	24,693	18,716	11,335
1959	39	134	0	0	1,063	36	10,065	0	18,214	24,654	20,640	7,241	4,318
1960	24	134	0	0	717	36	16,651	0	5,006	14,092	20,386	6,176	4,492
1961	7	425	0	0	1,063	42	7,123	0	13,780	9,714	19,160	6,577	5,341
1962	9	802	146	560	1,063	22	3,123	0	15,268	13,968	16,984	9,968	7,116
1963	31	564	146	255	1,063	22	13,687	0	13,854	27,005	20,014	11,212	23,513
1964	26	746	875	204	211	25	16,495	0	13,282	20,497	23,824	8,206	8,490
1965	6	802	0	226	242	42	11,450	0	13,854	25,662	8,915	7,073	4,951
1966	23	802	0	315	453	32	17,668	0	14,458	6,790	34,497	14,231	3,354
1967	11	575	0	290	330	37	16,172	0	13,314	22,725	7,982	3,385	4,494
1968	26	638	0	310	1,063	31	16,531	0	12,976	16,269	9,682	4,228	6,560
1969	11	134	0	320	177	24	2,523	0	5,161	25,155	17,742	3,509	22,324
1970	14	570	0	552	358	113	2,648	0	14,764	26,827	15,082	14,501	14,068
1971	18	1,100	0	335	963	30	7,709	0	15,060	27,986	37,425	15,654	24,796
1972	14	1,693	0	417	861	46	11,864	0	11,824	12,780	10,052	4,602	6,695
1973	83	1,347	0	1,099	1,849	181	20,205	5,109	17,145	29,527	29,401	16,263	8,147

Table 19b. Pumping Estimates – Structural Geology Model
Zones 14 to 25 and Annual Totals, Years 1948 to 1973 (Zone Locations in Figure 34)
(all values in AF/yr)

Year	Zone												Total
	14	15	16	17	18	19	20	21	22	23	24	25	
1948	0	0	0	0	0	0	0	0	0	0	0	0	24,797
1949	0	35,549	0	0	0	0	0	0	0	0	0	0	60,190
1950	0	17,282	5,657	0	0	0	0	0	0	0	0	5,115	52,659
1951	0	0	0	0	0	0	0	0	0	0	0	1,072	33,045
1952	0	0	0	0	0	0	299	0	0	0	0	1,280	46,705
1953	0	0	0	0	364	1,843	543	0	0	0	0	2,559	69,180
1954	0	0	0	0	906	1,908	1,498	0	0	0	0	908	70,639
1955	0	0	3,452	0	1,454	2,404	177	0	0	0	0	1,558	88,338
1956	0	0	3,199	0	1,834	1,849	307	0	0	0	48	585	77,539
1957	0	0	3,109	0	1,782	1,631	1,973	0	0	0	184	1,227	102,794
1958	0	0	5,952	0	526	452	177	0	0	0	184	765	96,554
1959	0	0	0	0	2,353	638	173	0	12	0	27	1,606	91,213
1960	0	0	2,445	0	236	695	408	0	15	0	184	1,125	72,822
1961	16,010	0	2,285	0	297	510	126	0	46	0	67	912	83,485
1962	9,034	0	0	0	280	933	186	0	20	0	54	1,091	80,627
1963	11,381	0	0	0	445	1,003	701	0	67	0	184	954	126,101
1964	0	0	0	0	379	1,691	267	0	66	0	184	939	96,407
1965	0	0	0	0	347	443	380	0	34	0	184	977	75,588
1966	0	0	0	0	260	399	136	0	35	0	184	1,046	94,683
1967	0	0	3,398	0	492	553	293	0	42	0	43	1,281	75,417
1968	0	0	2,819	0	451	1,195	129	0	67	0	184	1,032	74,191
1969	17,585	0	0	0	289	2,053	193	0	11	0	184	895	98,290
1970	5,472	0	0	0	439	2,319	0	0	136	0	373	2,246	100,482
1971	5,005	0	0	0	371	459	0	0	19	0	253	1,824	139,007
1972	3,893	0	0	0	291	405	0	0	55	0	267	2,211	67,970
1973	5,138	0	2,852	0	507	1,204	0	0	24	0	399	2,441	142,921

Table 19c. Pumping Estimates – Structural Geology Model
Zones 1 to 13, Years 1974 to 2002 (Zone Locations in Figure 34)
(all values in AF/yr)

Year	Zone												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1974	0	861	572	669	533	202	1,799	14,339	7,183	10,848	9,365	8,557	8,756
1975	0	841	1,132	837	12	16	7,193	15,660	6,077	11,422	11,160	11,152	11,070
1976	0	1,001	5	37	571	0	9,385	14,522	7,273	9,193	14,258	8,439	7,194
1977	0	685	0	1,300	877	0	5,239	15,343	4,144	11,638	12,209	8,882	9,311
1978	0	897	0	1,200	1,254	0	4,391	12,592	5,290	9,364	13,726	7,590	8,346
1979	0	1,402	0	897	928	0	5,123	13,611	4,830	8,822	12,967	8,494	7,186
1980	0	1,474	0	32	1,104	0	6,796	11,419	5,403	11,991	21,464	12,703	8,539
1981	0	1,020	0	16	0	0	6,274	10,705	7,486	8,819	8,848	4,325	6,518
1982	0	945	0	408	40	0	5,307	10,927	5,968	10,644	12,138	4,298	9,709
1983	0	1,283	0	863	87	0	531	11,230	1,757	8,647	7,208	2,436	6,975
1984	0	1,327	0	694	9	0	99	9,366	1,495	8,233	3,663	3,483	5,089
1985	1	689	0	1,143	0	0	6,301	9,109	2,719	7,553	4,806	1,588	5,301
1986	1	91	0	61	306	115	528	9,514	861	7,400	4,479	4,151	7,138
1987	0	313	0	605	6	0	128	11,133	569	6,186	5,684	4,543	5,777
1988	1	1,045	0	804	182	18	601	9,100	737	8,566	5,243	5,097	7,213
1989	28	626	113	852	264	100	310	8,583	2,386	6,425	4,689	3,683	6,967
1990	62	344	227	928	498	216	312	7,370	4,185	7,277	6,403	2,786	4,855
1991	0	366	18	962	46	0	38	7,262	855	4,973	7,182	4,525	5,075
1992	1	468	0	944	59	0	33	3,029	2,712	5,596	4,905	3,023	5,664
1993	1	337	0	411	50	3	30	3,947	1,365	5,112	5,128	2,736	4,559
1994	0	70	0	0	39	5	9	5,892	14	6,924	7,136	3,579	7,354
1995	0	104	0	0	5	1	8	5,945	16	9,796	11,014	6,577	10,027
1996	44	128	72	21	74	0	11	7,017	17	8,516	11,197	6,466	10,661
1997	0	63	4	0	17	0	39	2,504	0	9,764	15,463	8,315	12,174
1998	0	403	865	0	0	0	564	4,948	128	10,949	16,474	7,791	11,204
1999	0	157	1	217	22	1	706	2,592	7,873	11,870	12,316	10,612	8,791
2000	0	171	1,072	520	4	14	962	2,352	7,658	13,321	14,292	10,452	9,669
2001	0	82	535	345	1	0	956	2,839	8,654	12,763	17,667	11,702	9,597
2002	0	66	348	326	0	0	843	5,080	7,000	15,047	13,346	11,631	11,012

Table 19d. Pumping Estimates – Structural Geology Model
Zones 14 to 25 and Annual Totals, Years 1974 to 2002 (Zone Locations in Figure 34)
(all values in AF/yr)

Year	Zone												Total
	14	15	16	17	18	19	20	21	22	23	24	25	
1974	11,704	17,182	5,668	10,371	256	508	0	942	75	944	179	0	111,513
1975	13,139	16,286	7,428	9,241	330	607	449	1,488	0	1,008	341	0	126,889
1976	11,719	15,649	4,355	7,662	406	367	503	755	75	0	12	0	113,381
1977	12,341	17,622	7,586	9,976	210	1,062	1,027	1,472	0	46	247	0	121,217
1978	10,542	17,056	6,847	9,198	253	833	1,124	1,583	0	680	229	0	112,995
1979	7,928	16,538	6,214	8,507	154	619	986	1,144	0	1,523	318	0	108,191
1980	11,036	18,919	6,124	6,860	0	744	1,057	1,295	0	1,751	151	0	128,862
1981	6,492	11,446	4,252	6,466	0	0	203	476	179	1,770	0	0	85,295
1982	11,568	20,884	4,526	9,988	557	0	372	599	101	1,212	2	0	110,193
1983	8,131	12,464	2,348	6,018	1,134	0	399	187	0	1,368	4	0	73,070
1984	8,303	10,701	2,878	6,962	1,021	0	571	0	0	1,123	1	0	65,018
1985	5,794	12,325	2,258	6,997	770	0	131	0	0	1,854	16	0	69,355
1986	9,232	14,916	2,686	8,886	902	1	580	718	0	1,556	31	0	74,153
1987	8,688	11,191	1,417	7,668	731	0	95	0	0	862	134	0	65,730
1988	7,705	17,918	3,151	10,135	713	0	901	0	0	2,226	1	0	81,357
1989	7,744	16,158	2,390	9,727	1,107	0	980	0	0	1,763	1	0	74,896
1990	9,557	15,003	3,122	10,202	743	0	1,202	0	0	1,848	1	0	77,141
1991	7,041	15,500	1,862	10,563	286	0	813	0	0	2,731	35	0	70,133
1992	4,164	14,853	1,305	6,583	0	0	860	0	0	1,796	22	0	56,017
1993	3,968	13,783	1,213	6,002	0	0	445	0	0	1,656	14	0	50,760
1994	5,539	17,341	1,003	9,845	0	0	0	0	0	1,453	0	0	66,203
1995	11,945	24,145	1,256	12,814	0	0	0	0	0	4,751	0	0	98,404
1996	16,333	24,737	2,488	14,483	0	0	979	0	0	3,991	16	0	107,251
1997	13,218	23,129	2,956	10,996	0	0	661	0	0	1,872	0	0	101,175
1998	13,879	20,654	2,597	9,323	753	0	1,316	0	0	5,666	350	0	107,864
1999	17,131	18,232	1,195	9,302	388	0	750	0	0	7,256	395	0	109,807
2000	18,329	21,692	1,456	10,353	550	0	0	0	0	7,338	210	0	120,415
2001	16,779	19,930	1,395	8,696	660	1	936	0	0	4,964	126	0	118,628
2002	12,881	17,034	3,288	7,016	1,565	0	1,185	0	0	6,047	170	0	113,885

Table 20a. Pumping Estimates – Isotope Geochemistry Model
Zones 1 to 13, Years 1948 to 1973 (Zone Locations in Figure 34)
(all values in AF/yr)

Year	Zone												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1948	0	0	0	0	0	0	0	0	0	0	0	24,458	0
1949	0	0	0	0	0	0	0	0	0	0	0	24,397	0
1950	0	0	0	0	0	0	0	0	0	0	0	24,388	0
1951	0	0	0	0	0	0	0	0	0	18,121	0	13,698	0
1952	0	0	0	0	0	0	0	0	0	12,622	24,981	7,569	0
1953	0	0	0	0	0	0	0	0	18,172	25,483	15,762	4,378	0
1954	0	0	0	0	0	0	11,707	0	12,807	15,219	11,899	9,482	4,326
1955	0	0	0	0	0	0	7,109	0	17,363	18,587	20,509	6,363	8,747
1956	0	0	0	0	0	126	22,824	0	12,125	7,330	11,023	7,628	8,694
1957	0	802	0	0	0	87	11,931	0	14,193	17,601	28,936	11,151	8,180
1958	39	606	0	0	0	114	23,890	0	12,585	18,065	28,407	11,599	4,366
1959	39	281	0	0	450	22	5,698	0	16,558	23,457	17,748	6,911	4,395
1960	39	134	0	0	177	100	14,947	0	5,785	13,807	20,387	6,215	4,110
1961	7	134	0	0	177	97	6,596	0	13,898	9,709	18,915	6,794	5,314
1962	6	802	146	361	501	22	5,847	0	13,660	14,191	15,816	10,505	7,505
1963	39	802	172	173	1,063	22	12,602	0	14,130	26,606	20,277	10,878	24,037
1964	38	450	875	232	327	53	16,238	0	13,304	19,947	23,422	8,707	8,366
1965	39	359	0	337	459	22	11,524	0	13,580	25,051	8,739	7,502	5,027
1966	39	310	0	311	1,063	22	17,484	0	14,497	6,435	34,742	14,196	3,354
1967	9	802	0	185	448	22	15,967	0	13,125	22,496	7,895	3,694	4,250
1968	39	802	0	252	309	76	16,267	0	13,024	16,799	9,717	4,386	5,774
1969	8	525	0	182	292	31	3,374	0	4,008	25,102	17,031	4,095	22,595
1970	41	1,110	0	402	358	115	2,648	0	13,926	26,337	14,482	15,123	14,276
1971	53	911	0	362	522	30	7,569	0	14,786	28,100	37,282	15,910	24,962
1972	73	954	0	677	1,817	46	12,031	0	11,738	12,153	9,918	4,883	6,919
1973	37	1,701	0	1,124	1,120	212	19,778	4,820	17,080	29,949	29,139	16,682	7,858

Table 20b. Pumping Estimates – Isotope Geochemistry Model
Zones 14 to 25 and Annual Totals, Years 1948 to 1973 (Zone Locations in Figure 34)
(all values in AF/yr)

Year	Zone												Total
	14	15	16	17	18	19	20	21	22	23	24	25	
1948	0	0	0	0	0	0	0	0	0	0	0	0	24,458
1949	0	35,835	0	0	0	0	0	0	0	0	0	0	60,232
1950	0	17,456	5,758	0	0	0	0	0	0	0	0	1,631	49,233
1951	0	0	0	0	0	0	0	0	0	0	0	6,280	38,099
1952	0	0	0	0	0	0	674	0	0	0	0	741	46,587
1953	0	0	0	0	530	1,107	283	0	0	0	0	1,337	67,052
1954	0	0	0	0	772	1,503	360	0	0	0	0	823	68,898
1955	0	0	3,452	0	2,169	1,413	585	0	0	0	0	899	87,196
1956	0	0	3,199	0	2,113	2,239	177	0	0	0	115	1,871	79,464
1957	0	0	3,109	0	1,916	1,594	690	0	0	0	99	1,839	101,326
1958	0	0	7,665	0	810	452	177	0	0	0	184	981	109,295
1959	0	0	0	0	830	1,068	408	0	31	0	38	603	78,217
1960	0	0	2,742	0	405	757	123	0	34	0	184	1,154	70,927
1961	15,538	0	2,625	0	305	555	804	0	67	0	184	1,139	82,717
1962	8,547	0	0	0	327	1,050	130	0	67	0	184	1,178	80,037
1963	11,038	0	0	0	597	1,039	517	0	33	0	154	1,178	124,516
1964	0	0	0	0	528	1,722	214	0	33	0	184	1,148	95,300
1965	0	0	0	0	388	418	634	0	64	0	114	1,155	75,014
1966	0	0	0	0	260	463	136	0	48	0	184	1,204	94,399
1967	0	0	3,492	0	573	784	188	0	67	0	56	1,188	74,430
1968	0	0	3,222	0	372	763	632	0	39	0	120	1,167	72,919
1969	17,167	0	0	0	383	2,244	131	0	66	0	184	1,144	98,029
1970	5,153	0	0	0	573	2,413	0	0	25	0	373	2,380	98,584
1971	4,863	0	0	0	426	578	0	0	15	0	220	1,657	137,282
1972	3,630	0	0	0	374	341	0	0	142	0	138	2,419	67,226
1973	5,345	0	3,039	0	464	1,304	0	0	24	0	308	2,538	140,784

Table 20c. Pumping Estimates – Isotope Geochemistry Model
Zones 1 to 13, Years 1974 to 2002 (Zone Locations in Figure 34)
(all values in AF/yr)

Year	Zone												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1974	0	646	572	781	533	202	1,800	13,757	5,754	10,909	9,325	9,363	9,056
1975	0	841	1,383	837	12	12	7,015	15,740	6,077	10,566	11,873	9,052	11,202
1976	0	1,335	5	37	571	0	8,867	14,439	7,709	8,795	14,207	8,598	7,607
1977	0	685	0	1,110	1,023	0	4,883	15,285	4,144	10,857	12,651	8,003	9,896
1978	0	1,196	0	1,200	784	0	4,494	12,731	5,070	9,129	13,166	7,900	8,573
1979	0	1,411	0	921	1,090	0	4,285	12,964	5,347	7,697	13,439	8,178	7,200
1980	0	1,474	0	26	791	0	6,796	12,755	8,104	10,824	21,990	9,302	9,835
1981	0	1,193	0	16	0	0	7,450	10,765	6,093	8,671	8,616	4,561	6,166
1982	0	1,234	0	392	40	0	4,585	11,053	6,147	9,709	11,984	5,069	10,981
1983	0	1,283	0	772	127	0	332	11,314	1,366	8,233	7,208	3,322	7,101
1984	0	1,304	0	700	13	0	159	8,855	1,091	7,528	3,507	3,538	5,234
1985	1	689	0	1,164	0	0	6,578	9,224	2,624	7,236	4,572	1,609	5,560
1986	1	85	0	61	291	115	404	9,550	843	7,091	4,552	4,156	7,083
1987	0	313	0	612	9	0	136	11,224	657	5,970	5,792	3,731	5,874
1988	1	1,211	0	722	182	18	520	9,377	651	7,846	5,113	4,969	8,001
1989	28	626	113	823	262	100	411	8,606	2,109	6.462	4,448	4,094	6,812
1990	62	344	227	904	425	216	283	7,638	3,894	7,253	6,128	2,856	4,961
1991	0	488	18	915	74	0	26	7,642	1,160	4,465	7,328	4,055	4,857
1992	1	568	0	893	94	0	33	3,138	2,584	5,846	4,711	3,472	5,410
1993	1	253	0	411	77	3	30	3,954	1,211	4,444	5,070	2,971	4,718
1994	0	93	0	0	54	5	9	5,886	10	6,657	7,246	3,347	7,369
1995	0	103	0	0	6	1	8	6,283	13	9,575	11,135	6,454	9,870
1996	44	96	72	21	46	0	13	7,017	11	8,578	11,328	6,093	10,344
1997	0	61	4	0	24	0	51	2,769	0	9,519	15,178	8,334	12,118
1998	0	398	865	0	0	0	545	5,157	187	10,681	16,287	7,983	11,458
1999	0	118	1	217	15	1	843	2,409	7,557	11,884	12,082	11,024	8,485
2000	0	162	1,072	520	3	14	913	2,451	7,953	13,048	14,658	9,447	9,921
2001	0	85	535	345	1	0	942	1,893	8,356	12,755	17,763	11,710	10,189
2002	0	66	348	326	0	0	923	3,387	6,919	14,775	13,723	11,410	11,177

Table 20d. Pumping Estimates – Isotope Geochemistry Model
Zones 14 to 25 and Annual Totals, Years 1974 to 2002 (Zone Locations in Figure 34)
(all values in AF/yr)

Year	Zone												Total
	14	15	16	17	18	19	20	21	22	23	24	25	
1974	12,092	16,525	5,687	10,558	260	563	0	942	75	1,022	179	0	109,955
1975	13,417	16,594	7,365	9,481	312	607	426	1,250	0	991	227	0	124,439
1976	11,496	15,276	4,341	7,789	396	540	641	878	75	0	8	0	112,275
1977	12,244	17,773	7,629	9,847	228	789	865	1,701	0	53	247	0	119,228
1978	10,281	17,339	6,824	9,142	210	956	605	1,777	0	765	344	0	111,290
1979	8,234	16,729	6,301	8,494	175	435	1,222	1,431	0	1,480	318	0	105,940
1980	9,671	20,420	6,264	7,046	0	744	569	1,090	0	1,606	112	0	127,945
1981	6,484	11,850	4,427	6,363	0	0	203	714	179	1,668	0	0	84,226
1982	10,938	20,411	5,062	10,416	713	0	691	434	101	1,289	2	0	110,017
1983	7,970	11,626	2,756	6,376	1,064	0	662	187	0	1,462	5	0	71,883
1984	8,484	10,886	2,452	6,925	1,021	0	571	0	0	1,528	1	0	62,493
1985	5,851	12,519	2,074	7,209	830	0	96	0	0	1,863	16	0	69,025
1986	9,478	14,767	2,940	9,070	848	1	312	718	0	1,650	29	0	73,959
1987	8,660	11,668	1,204	7,760	671	0	114	0	0	941	118	0	65,141
1988	7,262	18,138	3,001	10,292	717	0	901	0	0	2,269	1	0	79,980
1989	7,654	16,133	2,703	9,797	1,107	0	528	0	0	1,964	1	0	74,127
1990	9,286	14,978	3,050	10,215	1,168	0	1,202	0	0	1,898	1	0	76,583
1991	6,707	15,733	2,140	10,589	286	0	556	0	0	2,912	35	0	69,498
1992	4,053	14,524	1,394	6,662	0	0	463	0	0	1,945	18	0	55,240
1993	4,153	13,293	1,097	6,280	0	0	341	0	0	2,000	14	0	50,067
1994	5,747	17,450	1,128	9,952	0	0	0	0	0	1,674	0	0	66,534
1995	11,692	24,203	1,655	12,873	0	0	0	0	0	4,797	0	0	98,565
1996	16,361	25,216	2,472	14,428	0	0	1,551	0	0	3,991	25	0	107,567
1997	13,017	23,270	3,022	11,134	0	0	1,227	0	0	2,011	0	0	101,678
1998	13,687	20,546	2,757	9,275	943	0	1,093	0	0	5,518	278	0	107,260
1999	17,173	18,191	1,279	9,316	558	0	1,323	0	0	7,171	395	0	109,924
2000	18,198	22,203	1,360	10,326	602	0	0	0	0	7,417	210	0	120,316
2001	16,902	19,793	1,251	8,738	660	1	804	0	0	4,845	102	0	117,585
2002	14,347	17,172	3,201	6,852	1,565	0	1,087	0	0	5,999	172	0	113,383

Table 21a. Pumping Estimates – Hybrid Model
Zones 1 to 13, Years 1948 to 1973 (Zone Locations in Figure 34)
(all values in AF/yr)

Year	Zone												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1948	0	0	0	0	0	0	0	0	0	0	0	24,324	0
1949	0	0	0	0	0	0	0	0	0	0	0	24,309	0
1950	0	0	0	0	0	0	0	0	0	0	0	24,294	0
1951	0	0	0	0	0	0	0	0	0	18,129	0	13,630	0
1952	0	0	0	0	0	0	0	0	0	12,596	24,896	7,586	0
1953	0	0	0	0	0	0	0	0	18,071	25,507	15,650	4,494	0
1954	0	0	0	0	0	0	11,603	0	12,846	14,992	11,849	9,520	4,495
1955	0	0	0	0	0	0	6,207	0	17,840	18,526	20,621	6,368	8,746
1956	0	0	0	0	0	73	22,760	0	12,227	7,124	11,100	7,649	8,794
1957	0	665	0	0	0	55	11,612	0	14,324	17,521	29,072	11,133	8,242
1958	39	785	0	0	0	25	23,890	0	18,252	13,017	28,219	8,350	5,259
1959	28	370	0	0	429	27	6,405	0	16,212	23,772	17,847	7,446	4,663
1960	6	197	0	0	177	43	14,657	0	5,862	13,755	20,155	6,376	4,170
1961	8	134	0	0	386	104	7,133	0	13,506	9,901	18,779	6,834	5,329
1962	6	240	146	585	604	31	6,124	0	13,276	14,378	15,558	10,735	7,310
1963	28	727	840	261	749	23	12,349	0	14,318	26,855	20,203	10,927	23,984
1964	17	777	556	169	253	66	16,276	0	13,282	20,129	23,466	8,701	8,357
1965	39	734	0	189	227	63	11,759	0	13,371	25,200	8,618	7,596	5,082
1966	23	190	0	303	435	25	17,419	0	14,622	6,646	34,780	14,176	3,354
1967	6	560	0	280	180	23	16,086	0	13,016	22,672	7,883	3,691	4,249
1968	27	230	0	368	466	39	16,247	0	13,065	16,838	9,721	4,381	5,808
1969	10	338	0	262	364	44	3,447	0	3,890	25,191	17,019	4,130	22,570
1970	13	765	0	454	358	44	2,651	0	13,970	26,431	14,423	15,135	14,319
1971	12	677	0	433	507	105	7,421	0	14,866	28,006	37,325	15,912	24,994
1972	30	1,247	0	550	1,114	91	11,941	0	11,861	12,158	9,947	4,819	7,030
1973	26	1,535	0	1,190	1,377	95	19,681	4,748	17,102	30,071	29,092	16,784	7,712

Table 21b. Pumping Estimates – Hybrid Model
Zones 14 to 25 and Annual Totals, Years 1948 to 1973 (Zone Locations in Figure 34)
(all values in AF/yr)

Year	Zone												Total
	14	15	16	17	18	19	20	21	22	23	24	25	
1948	0	0	0	0	0	0	0	0	0	0	0	0	24,324
1949	0	35,972	0	0	0	0	0	0	0	0	0	0	60,281
1950	0	17,562	5,818	0	0	0	0	0	0	0	0	2,613	50,287
1951	0	0	0	0	0	0	0	0	0	0	0	6,233	37,992
1952	0	0	0	0	0	0	298	0	0	0	0	853	46,229
1953	0	0	0	0	717	902	605	0	0	0	0	1,217	67,163
1954	0	0	0	0	780	1,665	538	0	0	0	0	1,193	69,481
1955	0	0	3,452	0	2,318	962	385	0	0	0	0	1,303	86,728
1956	0	0	3,199	0	2,354	1,467	292	0	0	0	121	1,209	78,369
1957	0	0	3,109	0	1,956	1,616	193	0	0	0	145	1,173	100,151
1958	0	0	7,720	0	1,279	547	225	0	0	0	116	1,114	108,013
1959	0	0	0	0	1,082	576	444	0	66	0	47	657	79,673
1960	0	0	2,724	0	418	678	628	0	47	0	184	1,158	71,032
1961	15,580	0	2,564	0	439	514	210	0	34	0	78	1,176	82,567
1962	8,647	0	0	0	475	921	152	0	57	0	135	1,161	80,295
1963	11,132	0	0	0	587	963	360	0	36	0	177	1,184	124,948
1964	0	0	0	0	654	1,661	197	0	15	0	168	1,175	95,125
1965	0	0	0	0	377	426	341	0	67	0	109	1,147	74,572
1966	0	0	0	0	261	390	179	0	46	0	184	1,165	93,985
1967	0	0	3,507	0	610	747	321	0	27	0	121	1,191	74,604
1968	0	0	3,230	0	391	902	331	0	52	0	100	1,149	73,088
1969	17,222	0	0	0	395	2,052	215	0	36	0	52	1,150	98,039
1970	5,129	0	0	0	620	2,273	0	0	33	0	322	2,370	98,532
1971	4,901	0	0	0	443	445	0	0	34	0	253	1,630	137,275
1972	3,616	0	0	0	386	392	0	0	51	0	302	2,453	66,711
1973	5,395	0	3,051	0	501	1,202	0	0	38	0	211	2,530	140,780

Table 21c. Pumping Estimates – Hybrid Model
Zones 1 to 13, Years 1974 to 2002 (Zone Locations in Figure 34)
(all values in AF/yr)

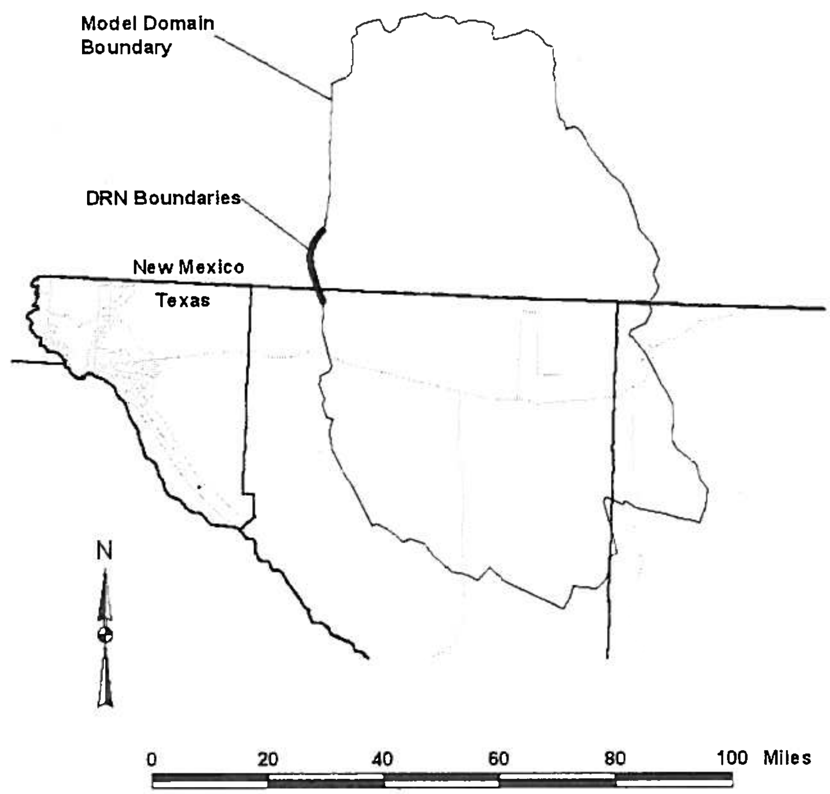
Year	Zone												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1974	0	861	646	727	566	197	1,905	13,755	5,581	10,868	9,166	9,611	9,093
1975	0	841	1,330	685	12	17	6,670	15,765	6,077	10,395	11,957	9,165	11,300
1976	0	1,335	5	30	622	0	8,624	14,543	7,986	8,466	13,977	8,768	7,857
1977	0	913	0	1,244	677	0	4,723	15,289	4,458	10,829	12,681	7,853	9,884
1978	0	897	0	1,157	784	0	4,470	12,712	5,058	9,116	13,031	8,057	8,529
1979	0	1,394	0	916	1,192	0	4,396	12,966	5,195	7,842	13,364	8,421	7,139
1980	0	1,498	0	26	690	0	7,914	12,826	6,143	11,376	20,243	10,583	9,816
1981	0	1,152	0	16	0	0	6,534	10,581	7,486	8,473	8,890	4,265	6,331
1982	0	1,182	0	408	40	0	4,847	11,198	6,147	9,464	11,935	5,268	11,176
1983	0	1,079	0	826	116	0	531	11,363	1,172	8,338	6,595	3,654	6,925
1984	0	1,333	0	719	13	0	159	8,632	1,223	7,163	3,753	3,290	5,985
1985	1	765	0	1,127	0	0	6,745	9,362	2,510	7,185	4,527	1,693	5,521
1986	1	91	0	50	348	115	399	9,454	850	6,917	4,528	4,174	7,214
1987	0	313	0	632	9	0	166	11,380	649	5,923	5,968	3,539	6,045
1988	1	1,211	0	722	182	18	528	9,426	695	7,659	4,985	4,840	8,256
1989	28	626	113	859	350	100	496	8,578	1,773	6,532	4,352	4,208	6,840
1990	62	382	227	871	325	216	341	7,675	3,604	7,395	5,968	3,016	4,899
1991	0	413	18	908	74	0	37	7,649	1,186	4,401	7,128	4,115	4,804
1992	1	568	0	938	59	0	31	3,175	2,589	5,789	4,627	3,653	5,354
1993	1	273	0	411	77	3	30	3,865	1,086	4,434	5,005	3,044	4,837
1994	0	93	0	0	52	5	6	5,731	16	6,672	7,088	3,420	7,446
1995	0	137	0	0	7	1	7	6,349	13	9,581	11,180	6,343	9,851
1996	44	129	72	21	71	0	13	7,017	11	8,410	11,247	6,210	10,366
1997	0	47	4	0	15	0	53	2,873	0	9,381	14,996	8,303	12,202
1998	0	406	865	0	0	0	628	5,171	127	10,715	16,091	8,061	11,345
1999	0	118	1	217	15	1	709	2,455	7,873	11,788	12,043	10,859	8,206
2000	0	128	1,072	520	2	14	977	2,094	7,637	13,140	14,657	9,666	9,990
2001	0	71	535	345	1	0	1,065	1,893	8,270	12,897	17,637	11,658	10,342
2002	0	66	348	326	0	0	999	4,119	6,584	14,918	13,152	12,003	11,178

Table 21d. Pumping Estimates – Hybrid Model
Zones 14 to 25 and Annual Totals, Years 1974 to 2002 (Zone Locations in Figure 34)
(all values in AF/yr)

Year	Zone												Total
	14	15	16	17	18	19	20	21	22	23	24	25	
1974	12,094	16,449	5,718	10,654	285	588	0	942	64	1,106	135	0	110,150
1975	13,431	16,544	7,421	9,481	310	607	451	1,329	0	959	303	0	124,209
1976	11,376	15,040	4,394	7,953	371	377	524	948	75	0	8	0	111,944
1977	12,249	17,824	7,700	9,888	226	891	675	1,563	0	54	247	0	118,955
1978	10,343	17,353	6,913	9,147	207	854	875	1,544	0	796	344	0	111,290
1979	8,249	16,681	6,301	8,466	166	550	1,118	1,319	0	1,540	318	0	106,139
1980	9,920	19,538	6,353	7,198	0	693	662	954	0	1,682	112	0	126,729
1981	6,400	11,940	4,392	6,456	0	0	267	598	179	1,703	0	0	84,511
1982	10,937	19,996	5,144	10,536	686	0	592	570	101	1,288	3	0	110,336
1983	8,170	11,677	2,775	6,564	986	0	419	144	0	1,478	4	0	71,737
1984	8,415	10,783	2,359	7,091	944	0	562	0	0	1,525	1	0	62,617
1985	5,808	12,458	2,172	7,214	888	0	109	0	0	1,864	16	0	69,199
1986	9,540	14,713	3,035	9,078	848	1	312	718	0	1,652	36	0	73,982
1987	8,531	11,709	1,209	7,690	703	0	162	0	0	981	98	0	65,394
1988	7,153	18,235	2,973	10,348	777	0	712	0	0	2,287	1	0	79,797
1989	7,692	16,118	2,700	9,945	939	0	705	0	0	1,990	1	0	74,291
1990	9,278	14,981	3,115	10,298	1,010	0	1,202	0	0	1,905	1	0	76,327
1991	6,817	15,806	2,151	10,686	286	0	752	0	0	2,941	23	0	69,782
1992	4,121	14,499	1,472	6,696	0	0	652	0	0	1,966	20	0	55,641
1993	4,238	13,199	1,076	6,357	0	0	288	0	0	2,013	14	0	49,977
1994	5,695	17,460	1,121	10,044	0	0	0	0	0	1,694	0	0	66,450
1995	11,659	24,282	1,741	12,864	0	0	0	0	0	4,783	0	0	98,661
1996	16,411	25,095	2,589	14,498	0	0	1,298	0	0	4,018	25	0	107,372
1997	12,918	23,452	3,048	11,159	0	0	1,026	0	0	2,034	0	0	101,464
1998	13,760	20,621	2,735	9,382	943	0	1,208	0	0	5,481	310	0	107,443
1999	17,256	18,417	1,354	9,319	471	0	1,253	0	0	7,142	395	0	109,774
2000	18,277	22,148	1,382	10,318	504	0	0	0	0	7,382	166	0	119,946
2001	16,985	19,760	1,231	8,873	660	1	829	0	0	4,858	126	0	117,966
2002	13,420	16,843	3,350	7,601	963	0	920	0	0	6,051	115	0	112,890

6.3.5 Drain (DRN) Package

The Drain Package was used to simulate outflow along a portion of the western boundary of the model as shown in Figure 35. Based on groundwater contours by Hibbs and others (1997), groundwater flows west outside the domain of the model (previously shown as Figure 10). The MODFLOW-2000 input file was written using a pre-processor program written in FORTRAN (*drn.exe*). This program was used during model calibration to adjust boundary head and conductance values. Figure 35 also includes the boundary head and conductance values estimated for each model.



Model	Boundary Head (ft)	Boundary Conductance (ft^2/day)
Structural Geology	4,187.76	9.57
Isotope Geochemistry	4,000.00	1.00
Hybrid	4,000.00	1.00

Figure 35. Location of DRN Boundaries and Parameter Estimates for each Model

6.3.6 Evapotranspiration (EVT) Package

Evapotranspiration from groundwater occurs under shallow water table conditions, such as the playa (Salt Flat). The area of evapotranspiration was estimated from the maximum area estimated by Groeneveld and Baugh (2002), and is shown in Figure 36. Maximum evapotranspiration rate was estimated to be 5.11 ft/yr, and the extinction depth was estimated to be 15 ft for all models.

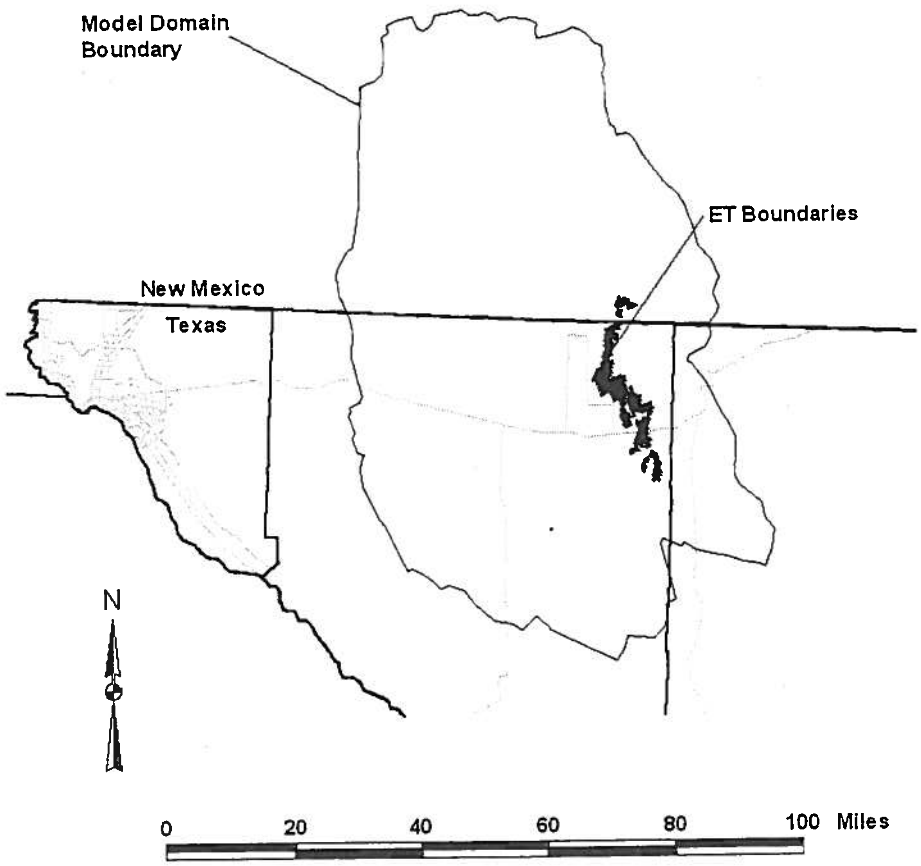
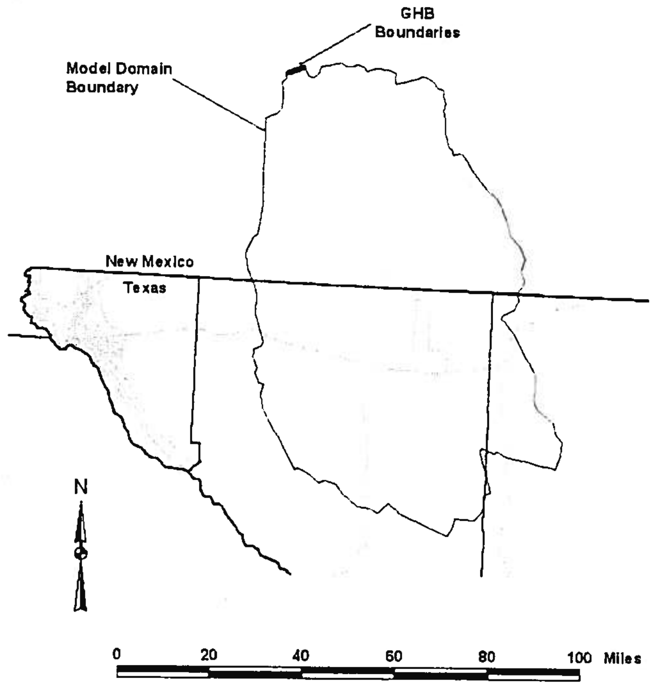


Figure 36. Area of Groundwater Evapotranspiration (ET)

6.3.7 General Head Boundary (GHB) Package

The GHB Package was used to simulate flow into the model domain in the high elevation area of the Sacramento Mountains (Figure 37). The pre-processor program, *ghb.exe* was used to write the MODFLOW-2000 input file during calibration to adjust boundary head and conductance values. The preprocessor reads the file *ghbin.dat* which contains estimates for the westernmost boundary cell (lowest head), the easternmost boundary cell (highest head) and the conductance.

For other boundary heads, the preprocessor interpolates linearly from west to east (lost to highest head). Figure 34 also summarizes the boundary head and conductance estimates for each model.



Model	Westernmost Boundary Head (ft)	Easternmost Boundary Head (ft)	Boundary Conductance (ft^2/day)
Structural Geology	8371.00	8000.00	380.37
Isotope Geochemistry	8371.00	8000.00	177.58
Hybrid	8371.00	8000.00	156.06

Figure 37. Location of GHB Boundaries and Parameter Estimates for each Model

6.3.8 Recharge (RCH) Package

Areal recharge to the model domain was simulated using the RCH package. A pre-processor program (*rch.exe*) was used to write the MODFLOW-2000 input files. For this model, recharge is defined as groundwater which originates as precipitation that falls within the model domain. Groundwater inflow from outside the model domain (from the north and the south) is handled by the GHB and CHD packages.

Average precipitation for each cell is estimated using the relationship previously presented:

*Average Precipitation = -6.91244 + (0.003996*Cell Elevation)*

where: Average precipitation is estimated in inches per year
Cell elevation is in ft MSL (read in file topelev.dat)

Annual variations in precipitation for the calibration period (1948 to 2002) were based on historic records. These factors are read from the file *annualprecipfactor.dat.* Precipitation is further corrected based on a dampening factor to slightly raise dry years and slightly decrease wet years. This is intended to simulate the lag time associated with travel time through the unsaturated zone. The dampening factor is adjustable and appears in the file *rechparam.dat.* Dampening factors were adjusted during early portions of model calibration. A dampening factor of 1.0 would result in all years having average precipitation. A dampening factor of 0 would result in no dampening. A factor of 0.1 was found to work well in this setting (relatively shallow water table in the recharge areas). The dampened annual recharge factors (using a dampening factor of 0.1) data are summarized in Figure 38.

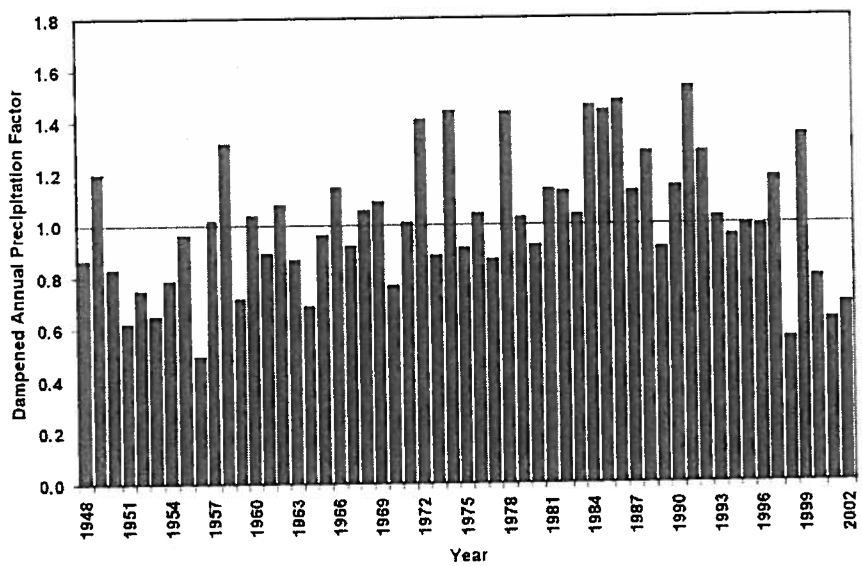


Figure 38. Annual Precipitation Factors with a Dampening Factor of 0.1

Annual recharge to each cell is estimated based on the corrected precipitation in a particular cell according to the data provided in the file *rechparam.dat.* Estimating recharge is based on a modified Maxey-Eakin approach (i.e. higher elevation areas have a higher recharge rate than lower elevation areas and higher precipitation years have a higher recharge rate than low precipitation years). The zones used for hydraulic conductivity and storativity (previously presented as Figures 31 to 33) were also used for recharge estimation.

For each zone, the pre-processor reads:

- The "Maxey-Eakin Elevation"
- The recharge rates associated with three precipitation groups

The "Maxey-Eakin" elevations for each model are summarized in Table 22. Above the Maxey-Eakin elevation, the higher recharge rates read in *rechparam.dat* are used. The following rates are applied to those areas that are above the Maxey Eakin elevation. If the precipitation is equal to or less than 7 in/yr, the recharge rate is set to 0% of precipitation. If the precipitation is between 7 and 15 in/yr, the recharge rate is set to 1% of precipitation. If the precipitation is between 15 and 25 in/yr, the recharge rate is set to 10% of precipitation. If the precipitation is greater than or equal to 25 in/yr, the recharge rate is set to 25% of precipitation. Below the Maxey-Eakin elevation, a standard recharge rate of is applied (assumed to be 0.005 in/yr).

Table 22. "Maxey-Eakin" Elevation Estimates for each Model (ft MSL)

Zone	"Maxey-Eakin" Elevation		
	Structural Geology Model	**Isotope Geochemistry Model**	**Hybrid Model**
1	7,364.65	5,400.00	5,400.00
2	5,522.27	5,400.00	5,400.00
3	5,400.00	5,400.00	5,400.00
4	5,393.45	5,400.00	5,400.00
5	4,858.83	4,881.30	4,881.30
6	5,415.16	5,400.00	5,400.00
7	5,015.63	5,400.00	5,400.00
8	5,400.00	5,400.00	5,400.00
9	5,170.29	5,400.00	5,400.00
10	5,400.00	5,400.00	5,400.00
11	5,296.77	5,400.00	5,400.00
12	5,697.70	5,400.00	5,400.00

The pre-processor writes MODFLOW-2000 input files for the specific model *(dvs.rch, dvi.rch, or dvh.rch)*. The pre-processor also sums all recharge in the model by zone and summarizes the results in terms of AF/yr in the file *sumrech.dat.* Annual recharge summaries for each zone for each of the models are presented in Tables 23 to 25. For each case, steady-state recharge was estimated under the assumption of 100 percent of average precipitation.

Table 23a presents recharge estimates for the structural geology model for the steady state conditions (pre-1948) and annual estimates for the years 1948 to 1974. Table 23b presents recharge estimates for the structural geology model for the years 1975 to 2002, and includes 1948 to 2002 averages for each zone. Table 24a presents recharge estimates for the isotope geochemistry model for the steady state conditions (pre-1948) and annual estimates for the years 1948 to 1974. Table 24b presents recharge estimates for the isotope geochemistry model for the years 1975 to 2002, and includes 1948 to 2002 averages for each zone. Table 25a presents recharge estimates for the hybrid model for the steady state conditions (pre-1948) and annual estimates for the years 1948 to 1974. Table 25b presents recharge estimates for the hybrid model for the years 1975 to 2002, and includes 1948 to 2002 averages for each zone.

Table 23a. Recharge Estimates for the Structural Geology Model (all values in AF/yr)
Steady State and Annual Estimates for Years 1948 to 1974 (Zone Locations Shown in Figure 31)

Year	1	2	3	4	5	6	7	8	9	10	11	12	Total
Steady State	0	2,963	0	9,564	656	411	3,112	7,785	195	0	34,927	2,871	62,485
1948	0	267	0	4,769	568	136	1,071	5,816	65	0	19,105	965	32,762
1949	1	3,550	0	13,897	7,765	639	14,369	18,655	902	0	46,157	3,439	109,375
1950	0	246	0	3,454	544	110	1,017	5,574	63	0	13,930	407	25,345
1951	0	185	0	796	408	33	747	1,297	47	0	2,234	179	5,925
1952	0	222	0	1,898	491	40	898	4,897	56	0	5,481	215	14,198
1953	0	193	0	967	426	35	779	2,091	49	0	2,331	186	7,057
1954	0	233	0	2,465	514	73	952	5,261	59	0	8,883	225	18,666
1955	0	1,298	0	8,120	633	315	1,688	7,165	127	0	32,379	2,767	54,493
1956	0	147	0	471	1	27	256	334	14	0	1,781	142	3,173
1957	0	3,016	0	10,029	668	543	3,877	8,389	209	0	35,900	2,922	65,554
1958	1	3,897	0	17,498	8,626	789	15,802	22,105	990	0	65,196	3,804	138,707
1959	0	211	0	1,544	467	38	855	4,084	54	0	3,427	204	10,885
1960	0	3,070	0	10,406	680	553	4,851	9,406	265	0	36,889	2,974	69,094
1961	0	338	0	5,818	585	182	1,136	6,026	88	0	22,954	1,559	38,689
1962	0	3,203	0	11,238	1,094	577	7,378	11,862	496	0	38,823	3,103	77,774
1963	0	267	0	4,769	568	136	1,071	5,816	65	0	19,105	965	32,762
1964	0	203	0	1,243	449	37	822	3,217	52	0	2,680	197	8,901
1965	0	1,298	0	8,120	633	315	1,688	7,165	127	0	32,379	2,767	54,493
1966	0	3,390	0	12,596	4,518	610	13,722	15,422	862	0	41,814	3,284	96,219
1967	0	464	0	6,604	603	250	1,296	6,353	91	0	27,036	1,942	44,640
1968	0	3,123	0	10,703	692	562	5,643	10,263	311	0	37,853	3,026	72,176
1969	0	3,229	0	11,389	1,394	581	8,124	12,508	759	0	39,175	3,129	80,290
1970	0	227	0	2,184	503	51	919	5,140	58	0	7,178	220	16,482
1971	0	2,990	0	9,812	662	466	3,482	8,144	207	0	35,408	2,896	64,067
1972	1	4,163	0	22,778	9,216	963	16,913	23,618	1,058	0	86,375	5,433	170,518
1973	0	314	0	5,513	579	159	1,114	5,937	87	0	21,766	1,379	36,851

Table 23b. Recharge Estimates for the Structural Geology Model (all values in AF/yr)
Years 1975 to 2002 and Zone Averages for 1948 to 2002 (Zone Locations Shown in Figure 31)

Year	1	2	3	4	5	6	7	8	9	10	11	12	Total
1974	1	4,299	0	24,614	9,452	1,017	17,375	24,223	1,085	0	96,056	6,125	184,248
1975	0	397	0	6,385	597	227	1,242	6,177	90	0	25,640	1,831	42,587
1976	0	3,096	0	10,554	686	557	5,132	9,747	267	0	37,376	3,000	70,416
1977	0	267	0	4,769	568	136	1,071	5,816	65	0	19,105	965	32,762
1978	1	4,272	0	24,231	9,393	1,011	17,267	24,072	1,079	0	93,539	6,001	180,866
1979	0	3,043	0	10,230	674	548	4,357	8,809	242	0	36,414	2,948	67,266
1980	0	464	0	6,604	603	250	1,296	6,353	91	0	27,036	1,942	44,640
1981	0	3,363	0	12,297	3,876	605	12,563	14,901	855	0	41,171	3,258	92,890
1982	0	3,337	0	12,057	3,053	601	11,290	14,439	848	0	40,702	3,232	89,559
1983	0	3,070	0	10,406	680	553	4,851	9,406	265	0	36,889	2,974	69,094
1984	1	4,439	0	25,585	9,570	1,059	17,621	24,525	1,128	0	100,893	6,432	191,254
1985	1	4,299	0	24,614	9,452	1,017	17,375	24,223	1,085	0	96,056	6,125	184,248
1986	1	4,552	0	27,315	9,688	1,158	17,867	24,828	1,170	0	105,977	7,608	200,165
1987	0	3,337	0	12,057	3,053	601	11,290	14,439	848	0	40,702	3,232	89,559
1988	1	3,790	0	16,198	8,390	711	15,341	21,472	963	0	58,685	3,671	129,222
1989	0	397	0	6,385	597	227	1,242	6,177	90	0	25,640	1,831	42,587
1990	0	3,390	0	12,596	4,518	610	13,722	15,422	862	0	41,814	3,284	96,219
1991	1	5,067	1	30,450	10,042	1,375	18,899	25,736	1,213	0	120,686	9,055	222,525
1992	1	3,790	0	16,198	8,390	711	15,341	21,472	963	0	58,685	3,671	129,222
1993	0	3,043	0	10,230	674	548	4,357	8,809	242	0	36,414	2,948	67,266
1994	0	1,090	0	7,869	627	302	1,600	7,041	116	0	31,367	2,741	52,755
1995	0	2,963	0	9,564	656	411	3,112	7,785	195	0	34,927	2,871	62,485
1996	0	2,936	0	9,279	650	366	2,878	7,687	173	0	34,376	2,845	61,191
1997	1	3,497	0	13,488	6,614	629	14,153	17,748	889	0	44,524	3,387	104,931
1998	0	166	0	531	362	30	671	502	42	0	2,008	160	4,472
1999	1	3,977	0	18,523	8,803	864	16,126	22,559	1,011	0	70,710	3,910	146,484
2000	0	235	0	2,639	520	85	962	5,332	60	0	9,795	238	19,867
2001	0	187	0	849	414	34	757	1,534	48	0	2,266	181	6,271
2002	0	206	0	1,332	455	37	833	3,571	52	0	2,872	199	9,559
1948-2002 Average	0	2,084	0	9,945	2,792	438	6,448	10,739	414	0	36,760	2,589	73,522

Table 24a. Recharge Estimates for the Isotope Geochemistry Model (all values in AF/yr)
Steady State and Annual Estimates for Years 1948 to 1974 (Zone Locations Shown in Figure 32)

Year	1	2	3	4	5	6	7	8	9	10	11	12	Total
Steady State	1,367	3,557	0	9,561	610	413	2,227	7,785	0	0	34,048	3,562	63,132
1948	163	445	0	4,766	528	138	306	5,816	0	0	18,954	1,025	32,142
1949	2,116	6,010	0	13,856	7,306	666	3,769	18,655	0	0	44,216	4,280	100,875
1950	147	416	0	3,451	506	112	283	5,574	0	0	13,796	465	24,751
1951	110	312	0	794	379	35	196	1,297	0	0	2,133	222	5,479
1952	132	375	0	1,896	456	42	236	4,897	0	0	5,360	267	13,662
1953	115	326	0	965	396	36	205	2,091	0	0	2,226	232	6,591
1954	139	394	0	2,462	478	75	258	5,261	0	0	8,756	280	18,104
1955	740	1,443	0	8,117	588	317	836	7,165	0	0	31,845	3,116	54,168
1956	88	249	0	469	1	28	157	334	0	0	1,701	177	3,203
1957	1,715	4,777	0	10,026	621	545	2,976	8,389	0	0	34,870	3,637	67,557
1958	2,322	6,597	0	17,454	8,020	819	4,167	22,105	0	0	63,065	4,727	129,276
1959	126	357	0	1,542	434	40	225	4,084	0	0	3,312	254	10,375
1960	1,829	5,197	0	10,371	632	576	3,259	9,406	0	0	35,528	3,701	70,501
1961	231	522	0	5,815	544	184	347	6,026	0	0	22,757	1,622	38,049
1962	1,909	5,423	0	11,201	1,044	601	3,401	11,862	0	0	37,071	3,862	76,375
1963	163	445	0	4,766	528	138	306	5,816	0	0	18,954	1,025	32,142
1964	121	344	0	1,240	418	38	216	3,217	0	0	2,569	245	8,409
1965	740	1,443	0	8,117	588	317	836	7,165	0	0	31,845	3,116	54,168
1966	2,020	5,739	0	12,558	4,466	636	3,599	15,422	0	0	39,960	4,087	88,488
1967	354	652	0	6,601	561	252	483	6,353	0	0	26,728	2,007	43,991
1968	1,861	5,287	0	10,667	643	586	3,316	10,263	0	0	36,146	3,766	72,535
1969	1,925	5,468	0	11,352	1,343	606	3,429	12,508	0	0	37,409	3,894	77,936
1970	136	384	0	2,181	467	53	242	5,140	0	0	7,054	274	15,932
1971	1,556	4,087	0	9,808	616	468	2,590	8,144	0	0	34,448	3,605	65,322
1972	2,481	7,048	0	22,731	8,569	995	4,481	23,618	0	0	84,098	6,419	160,441
1973	209	496	0	5,510	539	161	333	5,937	0	0	21,592	1,441	36,218

Table 24b. Recharge Estimates for the Isotope Geochemistry Model (all values in AF/yr)
Years 1975 to 2002 and Zone Averages for 1948 to 2002 (Zone Locations Shown in Figure 32)

Year	1	2	3	4	5	6	7	8	9	10	11	12	Total
1974	2,573	7,258	0	24,565	8,788	1,049	4,625	24,223	0	0	93,693	7,137	173,913
1975	309	584	0	6,382	555	229	437	6,177	0	0	25,366	1,895	41,935
1976	1,845	5,242	0	10,519	638	581	3,288	9,747	0	0	35,837	3,733	71,430
1977	163	445	0	4,766	528	138	306	5,816	0	0	18,954	1,025	32,142
1978	2,529	7,213	0	24,183	8,733	1,043	4,596	24,072	0	0	91,219	7,007	170,595
1979	1,813	5,152	0	10,195	627	571	3,231	8,809	0	0	35,220	3,669	69,288
1980	354	652	0	6,601	561	252	483	6,353	0	0	26,728	2,007	43,991
1981	2,004	5,694	0	12,259	3,823	631	3,571	14,901	0	0	39,332	4,055	86,270
1982	1,988	5,649	0	12,019	3,001	626	3,543	14,439	0	0	38,877	4,023	84,165
1983	1,829	5,197	0	10,371	632	576	3,259	9,406	0	0	35,528	3,701	70,501
1984	2,663	7,435	0	25,536	8,898	1,091	4,712	24,525	0	0	98,471	7,457	180,790
1985	2,573	7,258	0	24,565	8,788	1,049	4,625	24,223	0	0	93,693	7,137	173,913
1986	2,783	7,585	0	27,265	9,008	1,191	4,799	24,828	0	0	103,467	8,645	189,572
1987	1,988	5,649	0	12,019	3,001	626	3,543	14,439	0	0	38,877	4,023	84,165
1988	2,259	6,416	0	16,155	7,800	740	4,024	21,472	0	0	56,613	4,569	120,049
1989	309	584	0	6,382	555	229	437	6,177	0	0	25,366	1,895	41,935
1990	2,020	5,739	0	12,558	4,466	636	3,599	15,422	0	0	39,960	4,087	88,488
1991	3,205	8,211	1	30,398	9,337	1,410	5,353	25,736	0	0	117,793	10,130	211,573
1992	2,259	6,416	0	16,155	7,800	740	4,024	21,472	0	0	56,613	4,569	120,049
1993	1,813	5,152	0	10,195	627	571	3,231	8,809	0	0	35,220	3,669	69,288
1994	589	1,255	0	7,866	583	304	756	7,041	0	0	30,931	2,923	52,248
1995	1,367	3,557	0	9,561	610	413	2,227	7,785	0	0	34,048	3,562	63,132
1996	1,211	3,022	0	9,276	605	368	2,002	7,687	0	0	33,598	3,530	61,299
1997	2,083	5,920	0	13,448	6,559	656	3,712	17,748	0	0	42,613	4,216	96,956
1998	99	281	0	529	341	31	177	502	0	0	1,917	200	4,076
1999	2,370	6,732	0	18,478	8,185	894	4,252	22,559	0	0	68,536	4,853	136,859
2000	140	398	0	2,636	484	86	261	5,332	0	0	9,667	294	19,299
2001	112	317	0	847	385	35	199	1,534	0	0	2,164	225	5,818
2002	123	348	0	1,330	423	39	219	3,571	0	0	2,759	248	9,061
1948-2002 Average	1,229	3,386	0	9,925	2,625	451	2,142	10,739	0	0	35,705	3,076	70,536

Table 25a. Recharge Estimates for the Hybrid Model (all values in AF/yr)
Steady State and Annual Estimates for Years 1948 to 1974 (Zone Locations Shown in Figure 33)

Year	1	2	3	4	5	6	7	8	9	10	11	12	Total
Steady State	1,368	3,557	0	9,561	610	413	2,227	7,785	0	0	34,048	3,562	63,132
1948	164	445	0	4,766	528	138	306	5,816	0	0	18,954	1,025	32,142
1949	2,116	6,010	0	13,856	7,306	666	3,769	18,655	0	0	44,216	4,280	100,875
1950	147	416	0	3,451	506	112	283	5,574	0	0	13,796	465	24,751
1951	110	312	0	794	379	35	196	1,297	0	0	2,133	222	5,479
1952	133	375	0	1,896	456	42	236	4,897	0	0	5,360	267	13,662
1953	115	326	0	965	396	36	205	2,091	0	0	2,226	232	6,591
1954	139	394	0	2,462	478	75	258	5,261	0	0	8,756	280	18,104
1955	740	1,443	0	8,117	588	317	835	7,165	0	0	31,845	3,116	54,168
1956	88	249	0	469	1	28	157	334	0	0	1,701	177	3,203
1957	1,715	4,777	0	10,026	621	545	2,976	8,389	0	0	34,870	3,637	67,557
1958	2,323	6,597	0	17,454	8,020	819	4,166	22,105	0	0	63,065	4,727	129,276
1959	126	357	0	1,542	434	40	225	4,084	0	0	3,312	254	10,375
1960	1,830	5,197	0	10,371	632	576	3,259	9,406	0	0	35,528	3,701	70,501
1961	232	522	0	5,815	544	184	347	6,026	0	0	22,757	1,622	38,049
1962	1,909	5,423	0	11,201	1,044	601	3,401	11,862	0	0	37,071	3,862	76,375
1963	164	445	0	4,766	528	138	306	5,816	0	0	18,954	1,025	32,142
1964	121	344	0	1,240	418	38	216	3,217	0	0	2,569	245	8,409
1965	740	1,443	0	8,117	588	317	835	7,165	0	0	31,845	3,116	54,168
1966	2,020	5,739	0	12,558	4,466	636	3,599	15,422	0	0	39,960	4,087	88,488
1967	354	652	0	6,601	561	252	483	6,353	0	0	26,728	2,007	43,991
1968	1,861	5,287	0	10,667	643	586	3,316	10,263	0	0	36,146	3,766	72,535
1969	1,925	5,468	0	11,352	1,343	606	3,429	12,508	0	0	37,409	3,894	77,936
1970	136	384	0	2,181	467	53	242	5,140	0	0	7,054	274	15,932
1971	1,556	4,087	0	9,808	616	468	2,590	8,144	0	0	34,448	3,605	65,323
1972	2,481	7,048	0	22,731	8,569	995	4,481	23,618	0	0	84,098	6,419	160,441
1973	209	496	0	5,510	539	161	333	5,937	0	0	21,592	1,441	36,218

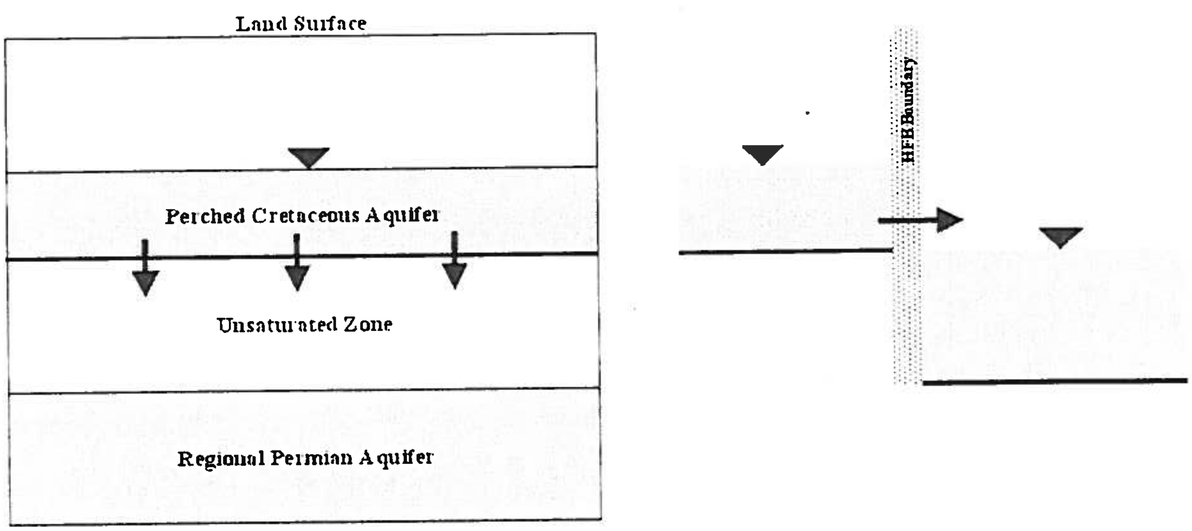
Table 25b. Recharge Estimates for the Hybrid Model (all values in AF/yr)
Years 1975 to 2002 and Zone Averages for 1948 to 2002 (Zone Locations Shown in Figure 33)

Year	1	2	3	4	5	6	7	8	9	10	11	12	Total
1974	2,574	7,258	0	24,565	8,788	1,049	4,625	24,223	0	0	93,693	7,137	173,913
1975	309	584	0	6,382	555	229	437	6,177	0	0	25,366	1,895	41,935
1976	1,845	5,242	0	10,519	638	581	3,288	9,747	0	0	35,837	3,733	71,430
1977	164	445	0	4,766	528	138	306	5,816	0	0	18,954	1,025	32,142
1978	2,529	7,213	0	24,183	8,733	1,043	4,596	24,072	0	0	91,219	7,007	170,595
1979	1,814	5,152	0	10,195	627	571	3,231	8,809	0	0	35,220	3,669	69,288
1980	354	652	0	6,601	561	252	483	6,353	0	0	26,728	2,007	43,991
1981	2,004	5,694	0	12,259	3,823	631	3,571	14,901	0	0	39,332	4,055	86,270
1982	1,988	5,649	0	12,019	3,001	626	3,542	14,439	0	0	38,877	4,023	84,165
1983	1,830	5,197	0	10,371	632	576	3,259	9,406	0	0	35,528	3,701	70,501
1984	2,664	7,435	0	25,536	8,898	1,091	4,712	24,525	0	0	98,471	7,457	180,790
1985	2,574	7,258	0	24,565	8,788	1,049	4,625	24,223	0	0	93,693	7,137	173,913
1986	2,783	7,585	0	27,265	9,008	1,191	4,799	24,828	0	0	103,467	8,645	189,572
1987	1,988	5,649	0	12,019	3,001	626	3,542	14,439	0	0	38,877	4,023	84,165
1988	2,259	6,416	0	16,155	7,800	740	4,024	21,472	0	0	56,613	4,569	120,049
1989	309	584	0	6,382	555	229	437	6,177	0	0	25,366	1,895	41,935
1990	2,020	5,739	0	12,558	4,466	636	3,599	15,422	0	0	39,960	4,087	88,488
1991	3,205	8,211	1	30,398	9,337	1,410	5,353	25,736	0	0	117,793	10,130	211,574
1992	2,259	6,416	0	16,155	7,800	740	4,024	21,472	0	0	56,613	4,569	120,049
1993	1,814	5,152	0	10,195	627	571	3,231	8,809	0	0	35,220	3,669	69,288
1994	589	1,255	0	7,866	583	304	756	7,041	0	0	30,931	2,923	52,248
1995	1,368	3,557	0	9,561	610	413	2,227	7,785	0	0	34,048	3,562	63,132
1996	1,211	3,022	0	9,276	605	368	2,002	7,687	0	0	33,598	3,530	61,299
1997	2,084	5,920	0	13,448	6,559	656	3,712	17,748	0	0	42,613	4,216	96,956
1998	99	281	0	529	341	31	176	502	0	0	1,917	200	4,076
1999	2,370	6,732	0	18,478	8,185	894	4,252	22,559	0	0	68,536	4,853	136,859
2000	141	398	0	2,636	484	86	261	5,332	0	0	9,667	294	19,299
2001	112	317	0	847	385	35	199	1,534	0	0	2,164	225	5,818
2002	123	348	0	1,330	423	39	219	3,571	0	0	2,759	248	9,061
1948-2002 Average	1,229	3,386	0	9,925	2,625	451	2,142	10,739	0	0	35,705	3,076	70,536

6.3.9 Horizontal Flow Barrier (HFB) Package

The area of perched groundwater associated with the Cretaceous rocks in the southwest portion of the model domain is simulated with the Horizontal Flow Barrier (HFB) package. This area is not well studied, but it is apparent that groundwater flows from this area towards the Permian rocks of Diablo Plateau. The unsaturated zone between the perched aquifer in Cretaceous rocks and the regional Permian aquifer acts to restrict flow vertically.

Because this is single layer model (two-dimensional lateral flow), HFB boundaries were implemented to simulate flow from the Cretaceous rocks to the regional Permian aquifer system. The left side of Figure 39 diagrammatically depicts the vertically downward movement of groundwater from the perched Cretaceous aquifer across the unsaturated zone into the regional Permian aquifer. The right side of Figure 39 depicts how the HFB package was implemented. The regional Permian aquifer in the area of the Cretaceous aquifer is ignored. Implementation of the HFB package results in restricted movement of groundwater from the perched Cretaceous aquifer to the regional Permian aquifer based on the specified conductance of the boundary. Thus, the HFB boundary acts as an analog to the unsaturated zone. An advantage to this approach is that the model is required to maintain the heads in the Cretaceous unit and represent a realistic flow into the Permian rocks. The alternative to this approach is to specify a flux across the boundary based on Darcian calculations.



Cross-Section of Perched Cretaceous Aquifer overlying Regional Permian Aquifer

Simulation of Movement Across HFB Boundary from Perched Cretaceous Aquifer to underlying Regional Permian Aquifer

Figure 39. Conceptual Diagram of Flow between the Perched Cretaceous Aquifer and the Regional Permian Aquifer

This conductance value was adjusted during the calibration process via the preprocessor *hfb.exe*. Conductance for the structural geology model was 4.10E-7 ft^2/day. Conductance for the isotope geochemistry model was 4.10E-7 ft^2/day. Conductance for the hybrid model was 3.87E-7 ft^2/day. The location of the HFB boundaries is shown in Figure 40.

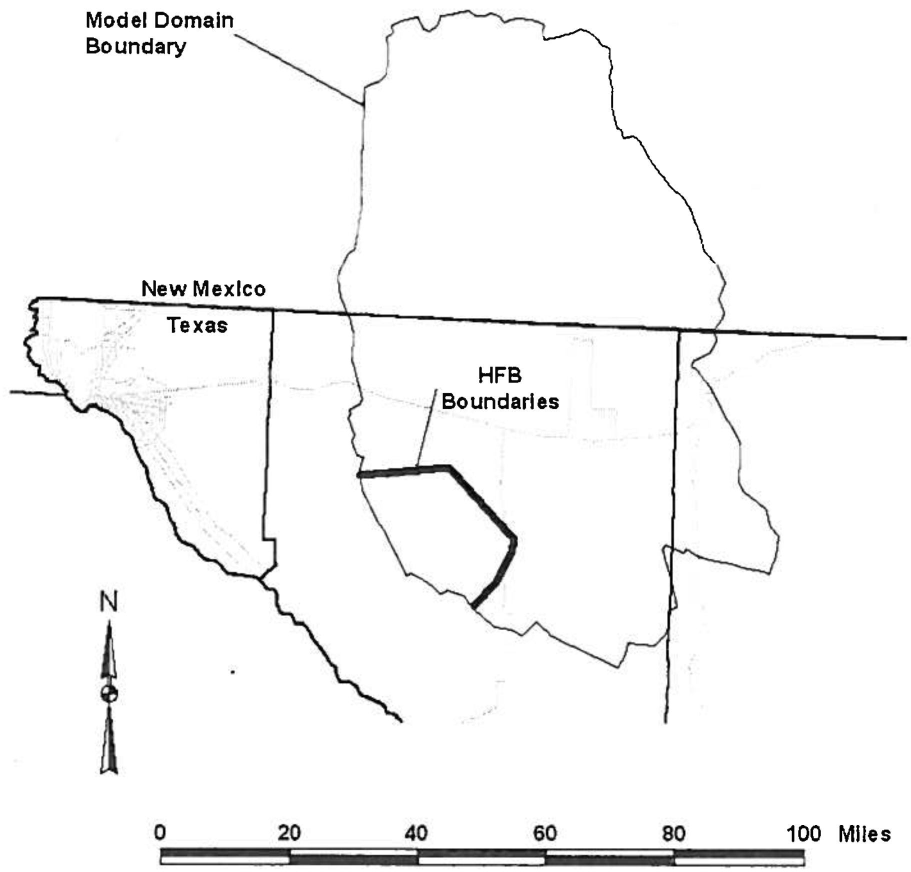


Figure 40. Location of HFB Boundaries

6.3.10 Constant Head Boundary (CHD) Package

The southeastern portion of the model includes the area where a groundwater divide exists, and likely contains outflow to areas southeast of the model domain. These characteristics were simulated using the CHD package of MODFLOW-2000, which includes the ability to vary the constant head by stress period. The locations of the boundaries in the context of the overall model domain are shown in Figure 41. Note that there are two distinct areas, a western group and an eastern group.

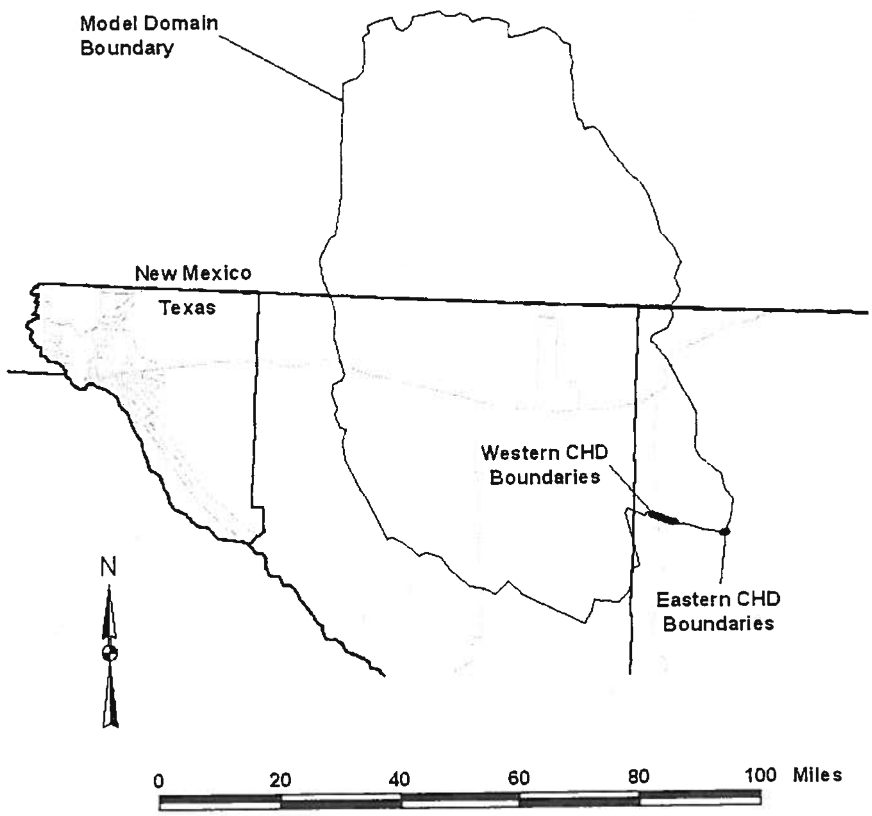


Figure 41. Location of CHD Boundaries

The boundaries were conceptualized based on an analysis of groundwater elevation data from monitoring wells that lie inside and south of the model domain. Groundwater elevation data is not taken on a frequent basis in these wells, so some averaging and interpolation was necessary. However, the following is evident from the analysis: 1) groundwater elevations are approximately equal in the area of the western CHD boundaries as this is the area of the groundwater divide, 2) groundwater elevations have been slightly dropping over time, and 3) groundwater outflow from the model domain is evident in the area of the eastern boundary. The eastern CHD boundary outflow would represent the hypothesized outflow of the area towards San Solomon Spring.

Figure 42 presents groundwater elevation contours representative of the time period 1973 to 1978, and Figure 43 presents groundwater elevation contours representative of the time period 1993 to 2003. For reference, the model boundary is shown in both figures.

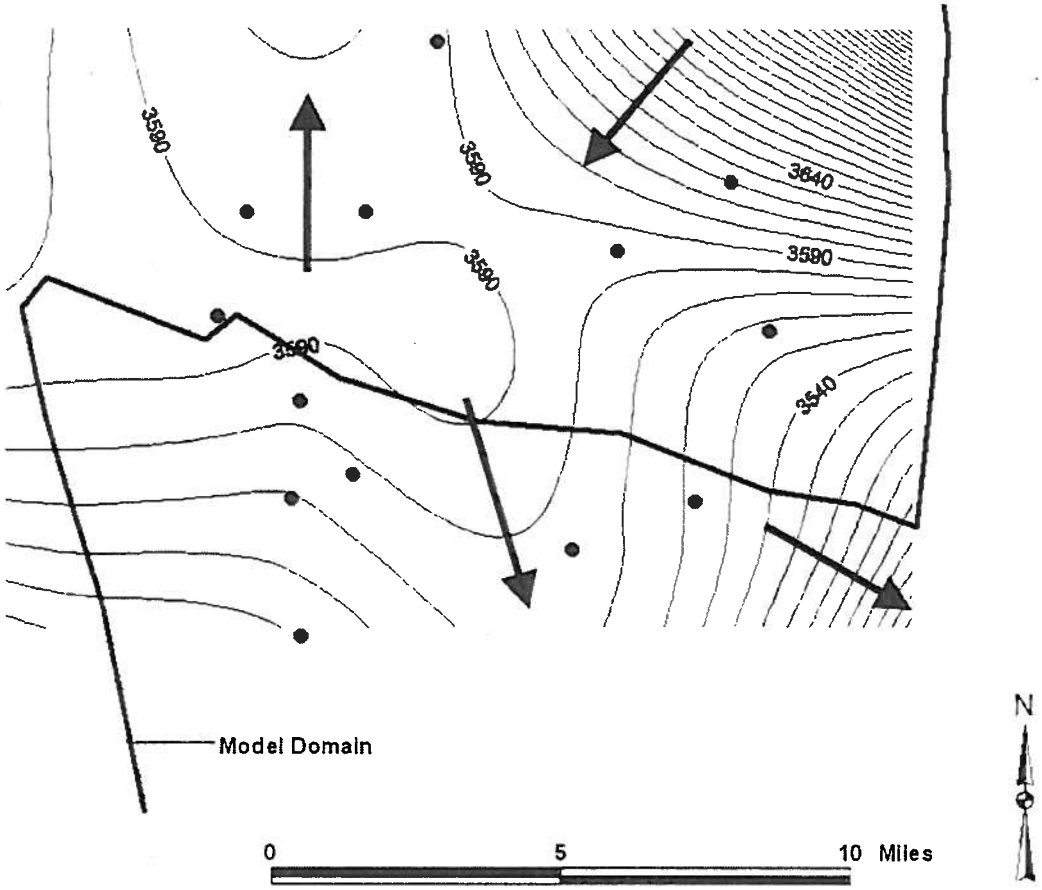


Figure 42. Groundwater Elevation Contours (ft MSL) and Interpreted Groundwater Flow Directions in Southeast Portion of Model Domain During period 1973 to 1978. Wells Used for Contouring are Shown as Dots

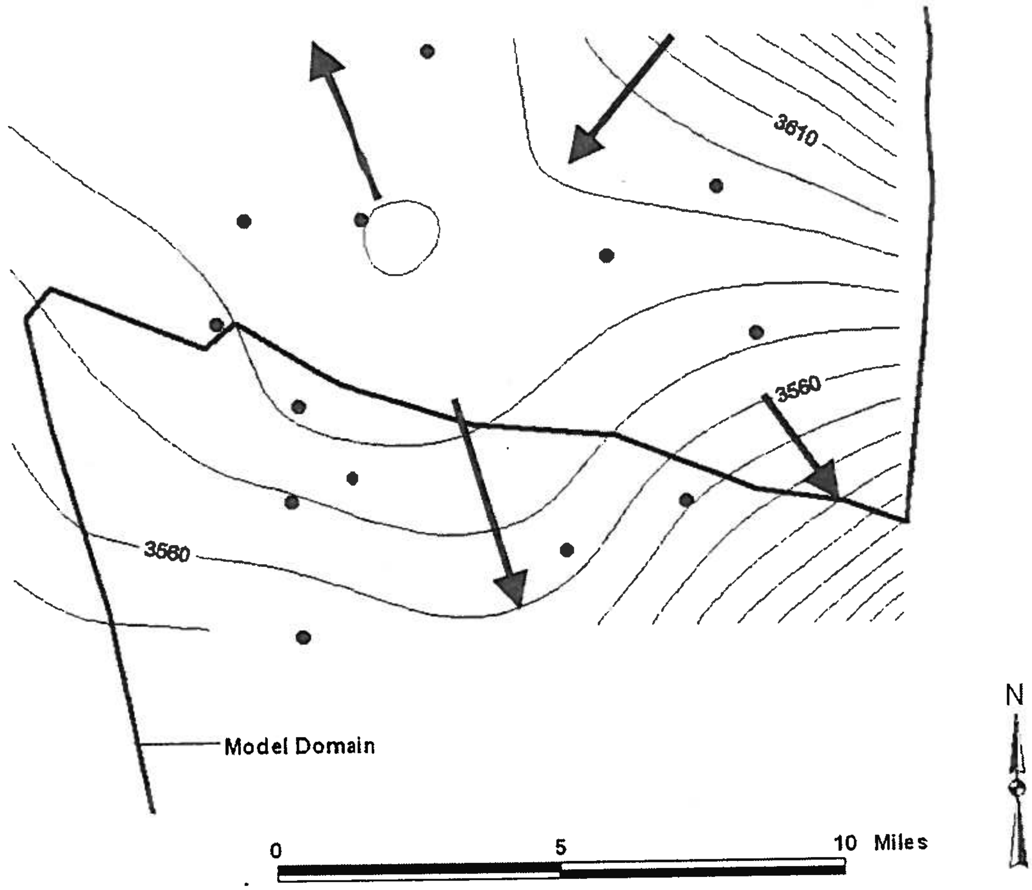


Figure 43. Groundwater Elevation Contours (ft MSL) and Interpreted Groundwater Flow Directions in Southeast Portion of Model Domain During period 1993 to 2003. Wells Used for Contouring are Shown as Dots

Based on this analysis, the western boundaries were set to an elevation of 3595.2 for 1948, and decreased 0.21 ft each year (i.e. each stress period). The eastern boundaries were set at 3520 ft and left constant for the entire calibration period.

6.3.11 Output Control (OC) Package

The Output Control Package contains specifications for how output is written. This particular version of the file specifies saving heads, drawdowns, and cell-by-cell flows for each stress period.

6.3.12 Geometric Multigrid Solver (GMG) Package

The Geometric Multigrid Solver package (Wilson and Naff, 2004) contains specifications for the chosen solver package. Note that in this particular implementation that the head closure criterion is 1.0E-03, and the residual closure criterion is 1.00.

7.0 MODEL CALIBRATION AND RESULTS

Calibration of the three groundwater flow models was accomplished by adjusting various parameters until model estimated groundwater elevations were in reasonable agreement with actual groundwater elevations. The calibration period was 1948 to 2002 (55 annual stress periods), with a steady-state stress period preceding the transient calibration (i.e. stress period 1) for a total of 56 stress periods. The steady state stress period was useful in that it provided an initial head solution that was used to initialize the transient simulation. The locations of the 369 wells that were used in the calibration are shown in Figure 44. These wells had at least groundwater elevation measurement from 1948 to 2002. The total number of groundwater elevation measurements from these 369 wells used in the calibration was 2,438. Table 26 summarizes the New Mexico wells (2 pages), and Table 27 summarizes the Texas wells (8 pages).

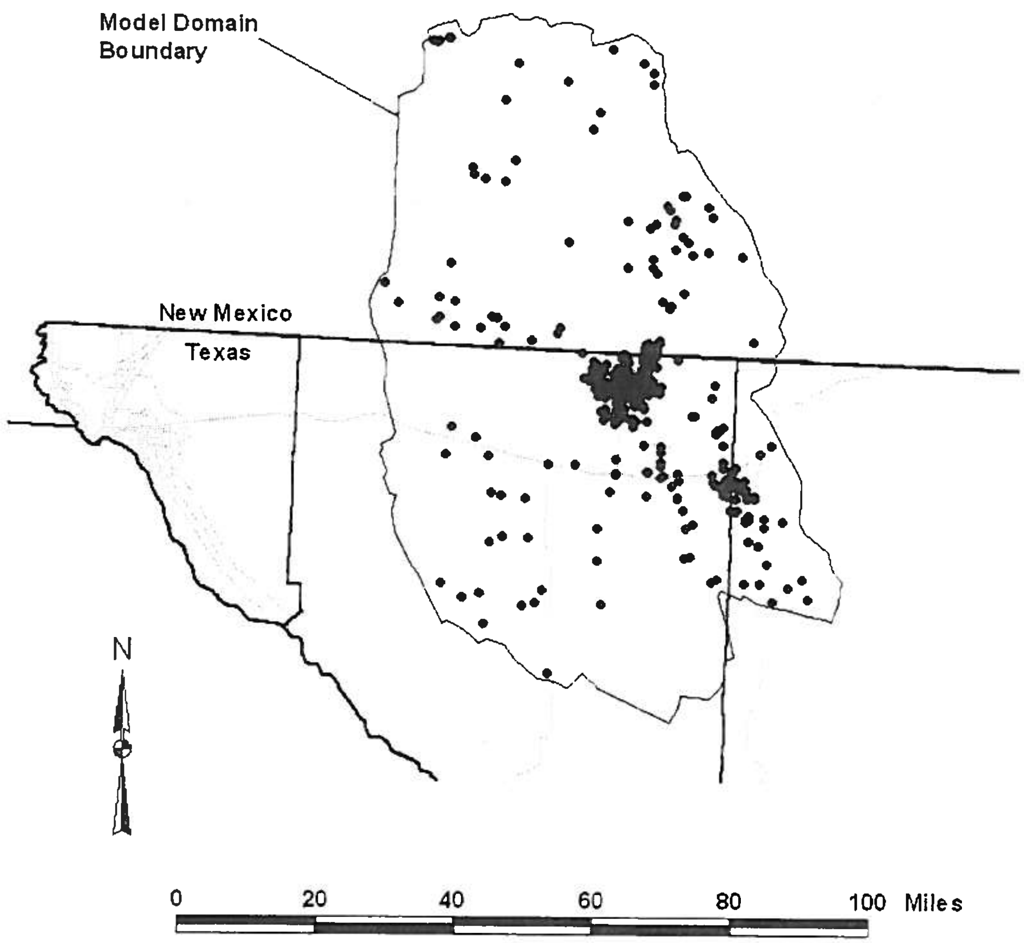


Figure 44. Location of Wells with Groundwater Elevation Measurements used in Model Calibration.

Table 26. New Mexico Calibration Well Summary (Page 1 of 2)

New Mexico Wells	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (ft MSL)	Lowest Groundwater Elevation (ft MSL)	Year of Earliest Measurement	Year of Latest Measurement
19S.12E.13.424	6	91	1	7310	7310	2000	2000
19S.12E.13.441	7	90	1	7293	7293	2000	2000
19S.12E.22.233	5	84	1	6950	6950	2000	2000
19S.12E.23.1	6	86	1	6947	6947	2000	2000
19S.12E.23.134	6	86	1	6919	6919	1999	1999
19S.14E.34.443	25	111	1	5865	5865	1963	1963
19S.16E.24.411	34	146	1	5961	5961	1983	1983
19S.17E.35.1	43	156	1	4930	4930	1964	1964
20S.14E.33.144	36	102	1	4879	4879	1947	1947
20S.15E.13.143	39	126	1	4620	4620	1951	1951
20S.17E.01.423	48	158	1	5088	5088	1956	1956
20S.17E.13.2	52	156	1	4791	4791	1964	1964
21S.16E.02.143	55	133	1	4566	4566	1953	1953
21S.16E.22.121	60	128	1	4017	4017	1960	1960
22S.13E.23.14	56	80	1	3725	3725	1958	1958
22S.13E.26.233	59	79	1	3829	3829	1969	1969
22S.14E.11.344	59	96	1	3843	3843	1949	1949
22S.14E.30.33	62	83	1	3822	3822	1959	1959
22S.14E.34.113	66	89	1	3926	3926	1969	1969
22S.18E.36.334	96	151	1	3621	3621	1959	1959
23S.17E.22.333	97	127	1	3716	3716	1960	1960
23S.18E.02.222	96	151	1	3668	3668	1967	1967
23S.18E.09.233	97	144	3	3635	3642	1956	1984
23S.18E.15.112	99	144	1	3611	3611	1967	1967
23S.18E.22.244	103	145	1	3616	3616	1972	1972
23S.18E.29.110	102	137	2	3629	3630	1979	1984
23S.18E.30.34	103	135	1	3787	3787	1949	1949
23S.19E.09.243	104	158	1	3640	3640	1981	1981
23S.19E.15.344	108	158	1	3596	3596	1960	1960
24S.13E.32.243	87	59	2	4601	4601	1959	1977
24S.16E.07.233	96	103	1	3696	3696	1960	1960
24S.17E.27.323	113	121	1	3574	3574	1957	1957
24S.18E.01.432	113	146	4	3608	3619	1977	1994
24S.18E.11.332	114	140	1	3654	3654	1957	1957
24S.18E.20.133	115	131	1	3603	3603	1973	1973
24S.18E.29.313	118	130	1	3620	3620	1963	1963
24S.18E.32.144	120	130	2	3609	3609	1979	1984
24S.19E.16.222	120	151	1	3720	3720	1962	1962
24S.19E.18.234	118	145	1	3637	3637	1953	1953
24S.20E.16.134	126	163	1	3551	3551	1977	1977

Table 26. New Mexico Calibration Well Summary (Page 2 of 2)

New Mexico Wells	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (ft MSL)	Lowest Groundwater Elevation (ft MSL)	Year of Earliest Measurement	Year of Latest Measurement
25S.11E.14.3	85	32	1	4696	4696	1964	1964
25S.12E.31.1	93	35	1	4734	4734	1961	1961
25S.13E.28.4	101	55	1	4555	4555	1947	1947
25S.13E.30.1	97	50	1	4728	4728	1958	1958
25S.18E.13.122	131	137	4	3606	3608	1977	1994
25S.18E.21.233	131	128	30	3593	3617	1958	1992
25S.18E.27.222	134	131	1	3621	3621	1955	1955
25S.18E.27.232	134	130	1	3618	3618	1965	1965
26S.12E.12.422	105	46	1	4645	4645	1962	1962
26S.13E.07.1	104	47	1	4537	4537	1965	1965
26S.13E.16.244	110	51	1	4668	4668	1949	1949
26S.14E.04.331	112	65	1	4637	4637	1951	1951
26S.14E.04.444	113	67	1	4612	4612	1975	1975
26S.14E.14.113	117	69	1	4583	4583	1960	1960
26S.14E.18.411	114	60	1	5084	5084	1981	1981
26S.14E.27.322	122	65	1	4589	4589	1962	1962
26S.15E.12.444	125	88	1	3671	3671	1960	1960
26S.15E.13.432	127	86	1	3796	3796	1962	1962
26S.15E.29.222	126	76	1	3696	3696	1958	1958
26S.18E.09.424	144	117	1	3578	3578	1949	1949
26S.18E.19.433	144	116	1	3581	3581	1957	1957
26S.18E.21.124	144	122	1	3591	3591	1948	1948
26S.18E.21.223a	131	128	2	3585	3627	1948	1951
26S.18E.21.313	145	120	44	3598	3626	1955	1999
26S.18E.21.333	146	120	1	3594	3594	1948	1948
26S.18E.21.411	145	121	1	3582	3582	1948	1948
26S.18E.28.113	146	119	18	3592	3617	1955	1973
26S.18E.28.131	147	119	1	3569	3569	1948	1948
26S.18E.29.111	145	117	7	3576	3615	1949	1999
26S.18E.29.113	145	117	1	3580	3580	1949	1949
26S.18E.30.122	144	117	22	3532	3557	1955	1994
26S.18E.30.321	145	115	24	3557	3582	1949	1999
26S.18E.32.122	147	118	26	3562	3588	1955	1984
26S.18E.33.111	148	119	1	3598	3598	1948	1948
26S.18E.33.133	148	119	1	3579	3579	1950	1950

Table 27. Texas Calibration Well Summary (Page 1 of 8)

Texas Wells	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (ft MSL)	Lowest Groundwater Elevation (ft MSL)	Year of Earliest Measurement	Year of Latest Measurement
47-01-401	168	135	1	3705	3705	1947	1947
47-01-701	172	132	1	3621	3621	1947	1947
47-09-101	186	128	1	3629	3629	1948	1948
47-09-201	184	132	1	3594	3594	1974	1974
47-09-202	185	132	1	3605	3605	1970	1970
47-09-203	184	129	1	3606	3606	1972	1972
47-09-204	185	129	1	3599	3599	1972	1972
47-09-205	185	129	1	3607	3607	1972	1972
47-09-206	185	130	1	3602	3602	1973	1973
47-09-207	185	129	2	3581	3589	1973	1974
47-09-502	191	129	1	3592	3592	1970	1970
47-09-702	200	121	2	3597	3600	1970	1971
47-09-801	197	126	13	3594	3613	1953	1972
47-09-802	202	128	4	3595	3614	1958	1973
47-09-803	203	128	2	3595	3599	1970	1971
47-09-805	197	126	2	3599	3611	1959	1971
47-09-806	197	127	5	3592	3602	1965	1973
47-09-807	199	126	1	3592	3592	1971	1971
47-09-901	201	129	7	3580	3608	1956	2000
47-09-902	202	129	2	3627	3642	1964	1964
47-09-903	201	129	1	3594	3594	1969	1969
47-09-904	201	131	2	3597	3607	1955	1968
47-10-401	199	141	1	3653	3653	1988	1988
47-10-501	198	146	1	3765	3765	1970	1970
47-13-102	203	121	2	3625	3626	1958	1966
47-17-201	205	126	6	3596	3608	1958	1978
47-17-202	206	122	45	3564	3612	1953	2002
47-17-203	207	126	33	3583	3614	1957	1995
47-17-204	205	124	4	3521	3611	1958	1971
47-17-205	206	123	43	3579	3625	1953	1999
47-17-206	206	126	41	3585	3613	1959	2002
47-17-207	206	123	2	3599	3605	1958	1971
47-17-208	204	126	2	3631	3633	1964	1971
47-17-209	204	126	10	3581	3599	1963	2002
47-17-211	204	124	2	3598	3600	1971	1973
47-17-214	205	124	1	3599	3599	1971	1971
47-17-215	209	122	1	3606	3606	1971	1971
47-17-216	203	125	1	3593	3593	1971	1971
47-17-217	204	121	1	3604	3604	1971	1971
47-17-218	210	123	10	3605	3608	1963	1973

Table 27. Texas Calibration Well Summary (Page 2 of 8)

Texas Wells	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (ft MSL)	Lowest Groundwater Elevation (ft MSL)	Year of Earliest Measurement	Year of Latest Measurement
47-17-301	209	128	4	3591	3600	1959	1992
47-17-302	209	128	38	3569	3607	1957	2002
47-17-303	209	128	4	3591	3603	1958	1992
47-17-304	206	129	32	3591	3608	1964	2000
47-17-307	207	128	2	3601	3604	1964	1971
47-17-312	207	132	1	3633	3633	1964	1964
47-17-313	208	129	1	3616	3616	1964	1964
47-17-314	209	128	1	3607	3607	1964	1964
47-17-315	204	128	2	3594	3600	1964	1964
47-17-317	205	127	27	3571	3607	1964	1995
47-17-318	207	128	2	3597	3599	1971	1973
47-17-319	206	129	1	3605	3605	1971	1971
47-17-320	210	131	2	3599	3603	1972	1973
47-17-321	210	130	1	3593	3593	1970	1970
47-17-321	210	130	1	3595	3595	1971	1971
47-17-322	211	130	1	3594	3594	1971	1971
47-17-601	216	125	30	3591	3627	1958	1994
47-17-602	216	124	4	3587	3603	1958	1973
47-17-604	216	125	2	3587	3594	1971	1973
47-17-605	215	122	1	3610	3610	1973	1973
47-17-606	212	126	1	3600	3600	1971	1971
47-17-607	213	130	1	3583	3583	1974	1974
47-17-903	221	126	10	3590	3622	1964	1973
47-17-904	220	127	1	3608	3608	1972	1972
47-18-101	214	133	1	3695	3695	1969	1969
47-18-402	214	133	2	3580	3588	1970	2001
47-18-404	220	128	4	3575	3590	1964	1973
47-18-705	220	127	11	3592	3599	1971	2002
47-18-706	221	127	4	3602	3629	1965	1993
47-18-707	220	128	6	3600	3631	1964	1993
47-18-801	226	132	1	3579	3579	1971	1971
47-18-802	223	133	2	3575	3583	1976	1992
47-18-901	227	139	1	3602	3602	1959	1959
47-25-801	238	106	1	3602	3602	1964	1964
47-25-802	238	108	1	3616	3616	1971	1971
47-26-101	228	125	3	3572	3602	1972	1993
47-26-102	232	127	1	3603	3603	1971	1971
47-26-501	239	128	3	3583	3589	1977	1993
47-26-701	243	117	2	3587	3592	1964	1972
47-26-702	245	122	2	3590	3590	1992	1993

Table 27. Texas Calibration Well Summary (Page 3 of 8)

Texas Wells	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (ft MSL)	Lowest Groundwater Elevation (ft MSL)	Year of Earliest Measurement	Year of Latest Measurement
47-26-901	251	132	1	3584	3584	1971	1971
47-27-401	250	138	1	3620	3620	1971	1971
47-27-701	257	137	1	3556	3556	1974	1974
47-34-201	253	124	1	3594	3594	1971	1971
48-06-201	138	92	23	3603	3660	1953	1988
48-06-301	142	95	1	3591	3591	1993	1993
48-06-302	146	93	2	3568	3595	1973	1993
48-06-303	144	96	1	3591	3591	1993	1993
48-06-304	145	94	1	3595	3595	1993	1993
48-06-305	147	96	1	3602	3602	1993	1993
48-06-601	149	91	14	3558	3602	1960	1993
48-06-602	149	95	3	3593	3596	1966	1968
48-06-604	147	89	1	3587	3587	1984	1984
48-06-605	147	90	2	3589	3597	1984	1993
48-06-606	147	93	1	3599	3599	1993	1993
48-06-608	148	94	1	3593	3593	1993	1993
48-06-609	149	93	1	3595	3595	1993	1993
48-06-610	152	92	1	3594	3594	1993	1993
48-06-901	156	92	1	3592	3592	1993	1993
48-07-101	146	98	15	3599	3625	1949	1968 .
48-07-102	148	97	25	3577	3602	1963	2002
48-07-107	145	99	1	3597	3597	1993	1993
48-07-109	148	103	17	3556	3612	1966	1992
48-07-110	149	102	1	3600	3600	1953	1953
48-07-111	150	101	7	3618	3622	1947	1950
48-07-112	150	101	2	3621	3623	1947	1948
48-07-203	145	106	50	3580	3625	1947	1995
48-07-204	150	106	1	3589	3589	1993	1993
48-07-205	150	103	6	3619	3623	1947	1950
48-07-206	146	105	43	3566	3634	1947	2002
48-07-207	149	104	41	3578	3605	1959	2002
48-07-208	146	107	3	3597	3636	1947	1963
48-07-209	144	106	2	3595	3613	1953	1993
48-07-213	148	107	3	3580	3608	1953	1993
48-07-214	151	106	26	3579	3603	1966	1993
48-07-217	145	107	2	3584	3619	1953	1973
48-07-218	144	107	1	3583	3583	1973	1973
48-07-219	146	108	2	3572	3583	1985	1996
48-07-220	150	105	1	3599	3599	1968	1968
48-07-301	148	113	45	3581	3625	1947	1995

Table 27. Texas Calibration Well Summary (Page 4 of 8)

Texas Wells	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (ft MSL)	Lowest Groundwater Elevation (ft MSL)	Year of Earliest Measurement	Year of Latest Measurement
48-07-302	152	114	1	3611	3611	1953	1953
48-07-303	148	113	7	3607	3616	1953	1960
48-07-304	154	113	42	3574	3614	1953	2002
48-07-305	150	114	10	3611	3626	1948	1957
48-07-306	154	114	3	3616	3624	1947	1953
48-07-307	152	113	1	3565	3565	1990	1990
48-07-308	152	111	1	3594	3594	1993	1993
48-07-309	154	113	1	3612	3612	1953	1953
48-07-313	150	112	1	3575	3575	1968	1968
48-07-314	148	116	1	3595	3595	1993	1993
48-07-315	152	111	1	3581	3581	1974	1974
48-07-318	151	114	1	3708	3708	1993	1993
48-07-402	155	96	29	3588	3619	1947	1973
48-07-403	151	100	25	3584	3624	1947	1974
48-07-404	152	100	16	3592	3616	1953	1993
48-07-405	153	98	47	3577	3624	1947	2002
48-07-408	152	97	9	3620	3625	1947	1951
48-07-409	156	99	1	3617	3617	1947	1947
48-07-410	156	98	4	3562	3618	1953	2000
48-07-411	153	98	6	3606	3621	1947	1948
48-07-412	152	96	8	3619	3622	1947	1949
48-07-414	154	94	25	3581	3604	1963	1994
48-07-417	150	96	2	3597	3609	1966	1993
48-07-418	151	95	33	3579	3603	1966	2002
48-07-420	153	95	1	3596	3596	1971	1971
48-07-423	153	100	6	3602	3625	1947	1948
48-07-427	154	95	1	3592	3592	1993	1993
48-07-501	156	101	51	3578	3626	1947	2002
48-07-502	156	104	55	3574	3621	1947	2002
48-07-503	157	102	5	3609	3615	1947	1952
48-07-504	154	101	36	3582	3626	1947	1984
48-07-505	156	101	26	3579	3616	1953	1992
48-07-507	153	102	8	3607	3619	1947	1955
48-07-508	155	101	2	3619	3628	1947	1948
48-07-509	157	102	2	3622	3624	1947	1948
48-07-510	158	103	1	3592	3592	1993	1993
48-07-511	156	103	2	3627	3628	1947	1948
48-07-512	156	104	5	3592	3621	1947	1948
48-07-513	159	104	1	3622	3622	1947	1947
48-07-516	153	102	37	3566	3601	1966	2002

Table 27. Texas Calibration Well Summary (Page 5 of 8)

Texas Wells	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (ft MSL)	Lowest Groundwater Elevation (ft MSL)	Year of Earliest Measurement	Year of Latest Measurement
48-07-521	153	105	1	3594	3594	1993	1993
48-07-522	153	102	2	3557	3569	1986	1996
48-07-526	156	105	1	3567	3567	1981	1981
48-07-527	154	103	1	3590	3590	1969	1969
48-07-601	158	110	1	3610	3610	1959	1959
48-07-603	156	110	18	3602	3624	1947	1962
48-07-604	158	109	5	3614	3626	1947	1953
48-07-606	154	108	55	3576	3627	1947	2002
48-07-607	160	108	40	3578	3606	1959	2002
48-07-610	158	110	9	3622	3624	1947	1950
48-07-611	154	108	4	3586	3626	1947	1948
48-07-612	157	107	2	3622	3623	1947	1948
48-07-613	161	107	9	3606	3620	1947	1957
48-07-614	161	107	3	3617	3620	1947	1951
48-07-615	161	107	2	3621	3621	1947	1948
48-07-616	156	109	8	3622	3624	1947	1950
48-07-619	158	110	1	3597	3597	1993	1993
48-07-623	160	111	1	3596	3596	1993	1993
48-07-624	159	108	1	3589	3589	1969	1969
48-07-626	159	111	1	3597	3597	1967	1967
48-07-627	159	106	1	3581	3581	1969	1969
48-07-628	159	106	1	3591	3591	1993	1993
48-07-631	155	110	1	3592	3592	1993	1993
48-07-632	156	107	1	3592	3592	1993	1993
48-07-633	156	112	1	3594	3594	1993	1993
48-07-702	157	97	9	3594	3609	1959	1993
48-07-703	161	92	5	3586	3616	1953	1961
48-07-705	161	92	10	3597	3607	1947	1955
48-07-706	161	97	13	3580	3610	1963	1976
48-07-708	164	96	29	3562	3599	1966	2002
48-07-709	156	93	1	3607	3607	1966	1966
48-07-712	161	91	1	3598	3598	1993	1993
48-07-714	157	94	2	3593	3612	1978	1993
48-07-801	159	102	37	3571	3621	1947	2002
48-07-802	159	102	2	3617	3618	1947	1948
48-07-803	162	98	47	3585	3625	1952	2002
48-07-804	160	100	2	3624	3626	1947	1948
48-07-805	163	98	6	3612	3620	1954	1960
48-07-806	160	101	4	3624	3624	1947	1949
48-07-809	159	101	1	3585	3585	1971	1971

Table 27. Texas Calibration Well Summary (Page 6 of 8)

Texas Wells	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (ft MSL)	Lowest Groundwater Elevation (ft MSL)	Year of Earliest Measurement	Year of Latest Measurement
48-07-810	160	102	1	3572	3572	1976	1976
48-07-811	165	98	1	3555	3555	1972	1972
48-07-812	165	98	1	3535	3535	1977	1977
48-07-813	161	103	2	3515	3600	1982	1993
48-07-814	164	99	1	3595	3595	1966	1966
48-07-815	163	99	1	3526	3526	1976	1976
48-07-901	162	110	40	3577	3602	1958	2002
48-07-902	165	105	9	3593	3616	1953	1993
48-07-903	165	105	8	3604	3616	1953	1962
48-07-904	164	103	42	3584	3617	1949	2002
48-07-905	164	103	6	3613	3625	1952	1957
48-07-908	164	105	15	3600	3623	1947	1966
48-07-910	165	106	1	3583	3583	1987	1987
48-07-914	162	106	1	3591	3591	1993	1993
48-07-916	167	106	1	3611	3611	1993	1993
48-08-101	150	118	5	3604	3613	1953	1960
48-08-102	151	116	31	3582	3601	1966	1998
48-08-103	153	117	1	3601	3601	1993	1993
48-08-201	154	125	1	3600	3600	1993	1993
48-08-401	159	113	15	3597	3621	1950	1993
48-08-402	161	116	4	3617	3618	1947	1953
48-08-403	158	113	2	3604	3610	1953	1993
48-08-405	163	114	1	3613	3613	1974	1974
48-08-406	159	112	1	3609	3609	1969	1969
48-08-407	162	113	1	3594	3594	1993	1993
48-08-408	163	114	1	3613	3613	1985	1985
48-08-902	176	122	1	3614	3614	1972	1972
48-08-903	176	123	1	3616	3616	1948	1948
48-12-502	153	42	1	3646	3646	1985	1985
48-12-701	155	30	1	3773	3773	1971	1971
48-12-901	162	44	1	3650	3650	1985	1985
48-14-702	173	64	2	3603	3619	1959	1985
48-14-801	177	74	1	3522	3522	1985	1985
48-15-101	165	90	2	3612	3614	1953	1963
48-15-102	168	94	3	3583	3595	1985	1993
48-15-103	168	94	3	3584	3595	1985	1993
48-15-104	167	94	2	3584	3586	1985	1987
48-15-105	164	93	1	3581	3581	1993	1993
48-15-201	169	100	37	3582	3607	1959	1999
48-15-202	167	96	9	3613	3632	1951	1956

Table 27. Texas Calibration Well Summary (Page 7 of 8)

Texas Wells	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (ft MSL)	Lowest Groundwater Elevation (ft MSL)	Year of Earliest Measurement	Year of Latest Measurement
48-15-203	167	96	36	3568	3617	1953	1995
48-15-204	167	99	1	3616	3616	1953	1953
48-15-301	171	100	41	3586	3612	1959	2002
48-15-302	172	105	25	3581	3604	1963	1993
48-15-303	168	101	1	3591	3591	1964	1964
48-15-305	170	102	1	3606	3606	1958	1958
48-15-306	171	100	1	3543	3543	1978	1978
48-15-307	170	100	1	3588	3588	1981	1981
48-15-601	180	101	2	3591	3594	1965	1993
48-15-801	180	89	3	3616	3621	1948	1952
48-15-902	190	98	32	3549	3590	1959	2002
48-16-402	183	107	25	3593	3617	1959	1993
48-16-403	184	106	1	3596	3596	1993	1993
48-16-702	188	105	25	3586	3608	1959	1994
48-16-703	190	104	1	3574	3574	1985	1985
48-16-705	190	99	2	3567	3581	1990	1993
48-16-805	195	109	2	3602	3603	1974	1985
48-20-601	175	40	1	3622	3622	1985	1985
48-21-401	177	43	1	3626	3626	1985	1985
48-21-502	182	51	1	3618	3618	1985	1985
48-23-101	191	82	1	3624	3624	1985	1985
48-23-201	186	87	2	3574	3574	1964	1985
48-23-202	186	87	7	3584	3602	1965	1971
48-23-701	203	73	1	3612	3612	1985	1985
48-24-101	193	102	1	3619	3619	1985	1985
48-24-201	197	108	1	3605	3605	1964	1964
48-24-202	198	105	1	3591	3591	1972	1972
48-24-203	194	104	1	3582	3582	1974	1974
48-24-401	198	95	1	3599	3599	1964	1964
48-24-501	203	106	1	3599	3599	1971	1971
48-24-502	204	106	1	3580	3580	1971	1971
48-24-601	208	106	1	3597	3597	1972	1972
48-24-901	215	107	1	3604	3604	1964	1964
48-24-904	215	104	1	3579	3579	1985	1985
48-27-801	192	33	1	4050	4050	1985	1985
48-28-301	192	33	1	4367	4367	1985	1985
48-29-101	192	38	1	4290	4290	1985	1985
48-29-102	192	38	1	4292	4292	1985	1985
48-29-103	192	38	1	4290	4290	1985	1985
48-29-104	192	38	1	4292	4292	1985	1985

Table 27. Texas Calibration Well Summary (Page 8 of 8)

Texas Wells	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (ft MSL)	Lowest Groundwater Elevation (ft MSL)	Year of Earliest Measurement	Year of Latest Measurement
48-29-301	196	47	2	3606	3625	1985	1985
48-30-401	214	68	2	3559	3731	1985	1985
48-32-301	226	102	1	3591	3591	1972	1972
48-32-601	226	102	1	3597	3597	1971	1971
48-32-602	225	99	1	3595	3595	1972	1972
48-36-101	200	10	1	4680	4680	1987	1987
48-36-201	208	15	1	4475	4475	1987	1987
48-36-301	209	22	1	4343	4343	1987	1987
48-36-601	220	19	2	4365	4470	1972	1985
48-37-301	219	35	1	4377	4377	1985	1985
48-37-302	220	40	3	4198	4200	1985	1985
48-38-101	217	45	1	4176	4176	1985	1985
48-39-101	230	63	2	3620	3620	1985	1985
48-46-401	247	34	1	3638	3638	1971	1971

The three models were calibrated individually using a combination of trial-and-error parameter adjustments and automated adjustments using PEST, an industry-standard inverse modeling software package (Doherty, 2004). Parameter adjustment generally focused on hydraulic conductivity (both x- and y-direction), storativity, "Maxey-Eakin" recharge elevation, general head boundary elevation and conductance (northern edge of the model), and drain boundary elevation and conductance (northwestern edge of the model). Other parameters that were adjusted with less focus included recharge rates, irrigation acreage, and constant head boundary elevation (southeastern edge of the model). Calibrated parameters for each of the models were previously presented in Section 6.

7.1 Model Estimated Groundwater Elevations vs. Measured Groundwater Elevations

Calibration of the models was partly evaluated through a series of comparisons between model estimated groundwater elevations and measured groundwater elevations. The residual is the difference between the measured groundwater elevation and the model estimated groundwater elevation. If the residual is positive, the measured groundwater elevation is higher than the model estimated groundwater elevation. If the residual is negative, the measured groundwater elevation is lower than the model estimated groundwater elevation.

This section begins with an analysis of the calibration results of the entire domain of all three models. Attention shifts to an analysis of the calibration results of all three models in the Dell City area, the main area of interest. Finally, selected hydrographs are presented that compare model estimated groundwater elevations with actual groundwater elevations. Hydrographs for all wells for which enough data points were available are presented in Appendix C.

7.1.1 Calibration Results for Entire Model Domain

A statistical summary of the calibration of all three models is presented in Table 28, which summarizes the minimum residual, maximum residual, and average residual for each of the models. The standard deviation of the residuals and the range of measured groundwater elevations are presented. A common statistical test to examine calibration is the standard deviation of the residuals (the difference between actual groundwater elevations and model estimated groundwater elevations) divided by the range of measured groundwater elevations. Rumbaugh (2003, pg. 178) suggested that a good calibration would yield a value less than 0.10 to 0.15. Note that this value is less than 0.01 for all models.

Table 28. Statistical Summary of the Calibration of All Three Models

Calibration Statistic	Structural Geology Model	Isotope Geochemistry Model	Hybrid Model
Minimum Residual (ft)	-256.65	-394.96	-458.24
Maximum Residual (ft)	642.67	557.22	518.65
Average Residual (ft)	4.00	2.37	4.79
Standard Deviation of Residuals	30.84	30.40	30.60
Range of Measured Groundwater Elevations (ft)	3595	3595	3595
Standard Deviation/Range	8.58E-03	8.45E-03	8.51E-03
Sum of Squared Residuals	2.36E+06	2.27E+06	2.34E+06
Percentage of Residuals Within:			
± 10 ft	56.4	61.7	63.4
± 25 ft	94.5	93.1	92.5
± 50 ft	98.4	98.3	98.4

The summary also includes the value of the sum of squared residuals, which was used as the objective function during parameter estimation. Finally, the summary includes the frequency of residuals within 10 ft, 25 ft and 50 ft. Graphical summaries of the match between measured groundwater elevations and model estimated groundwater elevations are presented in Figures 45 to 47. Histograms of the residuals for each of the three models are presented in Figure 48 to 50. Note that the statistics of calibration and these overall graphical summaries for all three models are similar, and it is not possible to identify a model that is significantly better than the other two.

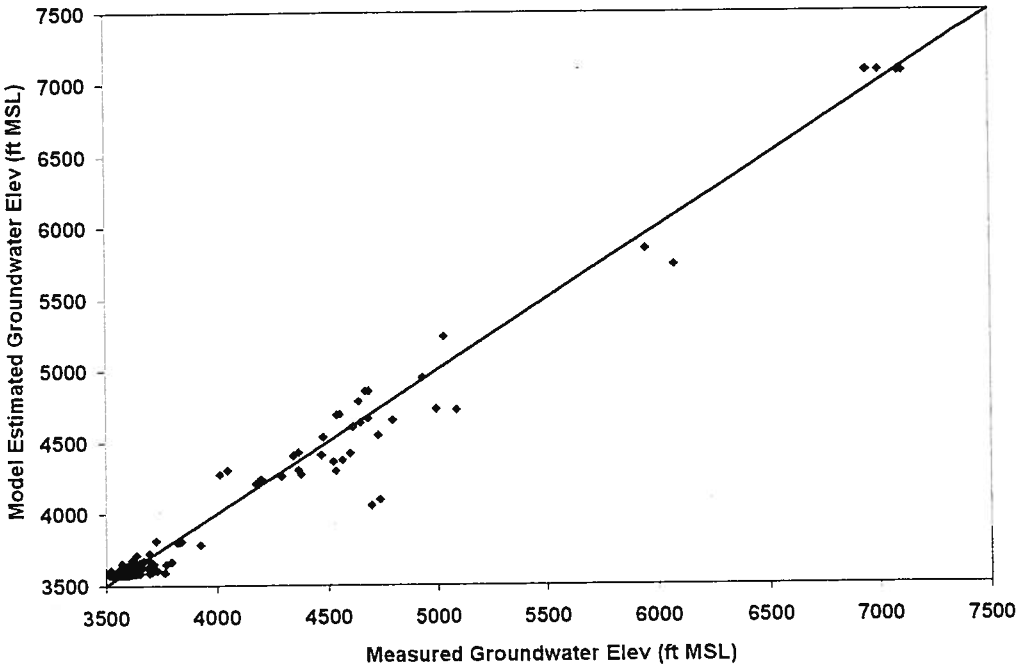


Figure 45. Measured Groundwater Elevations vs. Model Estimated Groundwater Elevations
Structural Geology Model

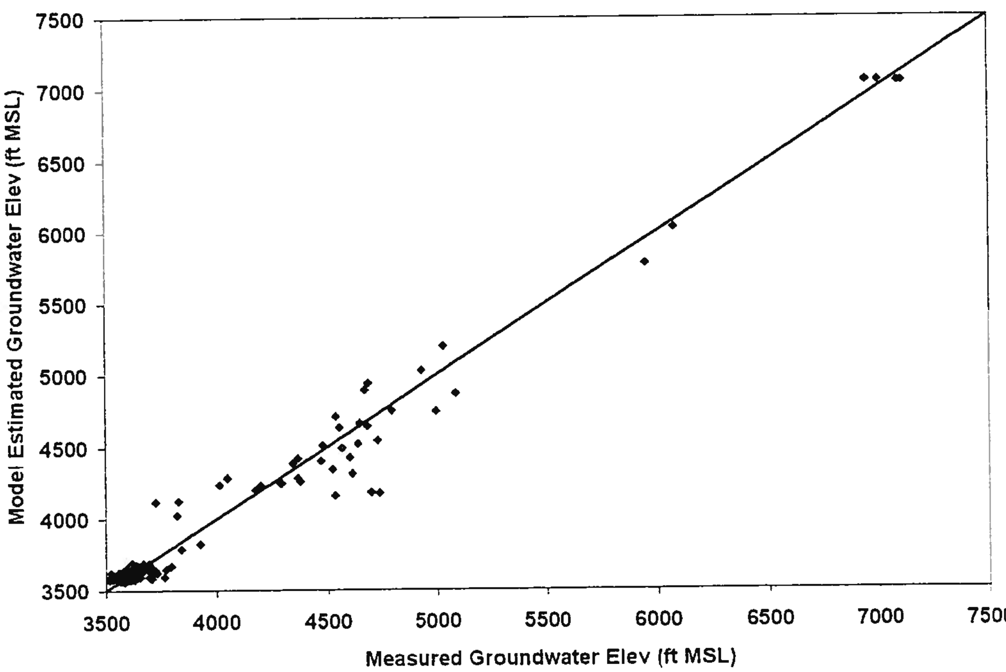


Figure 46. Measured Groundwater Elevations vs. Model Estimated Groundwater Elevations
Isotope Geochemistry Model

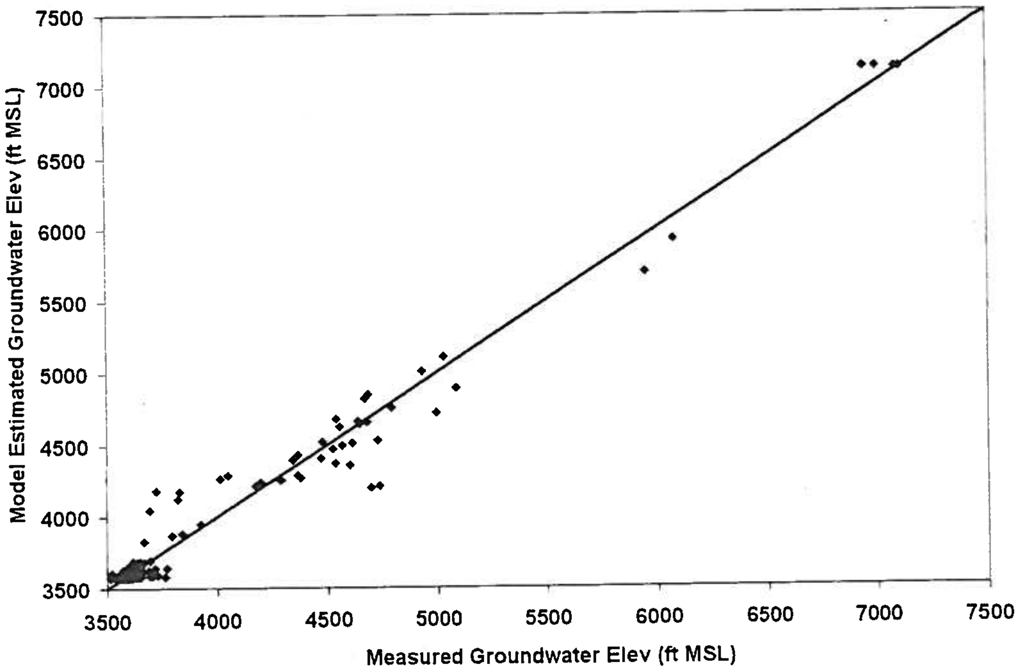


Figure 47. Measured Groundwater Elevations vs. Model Estimated Groundwater Elevations
Hybrid Model

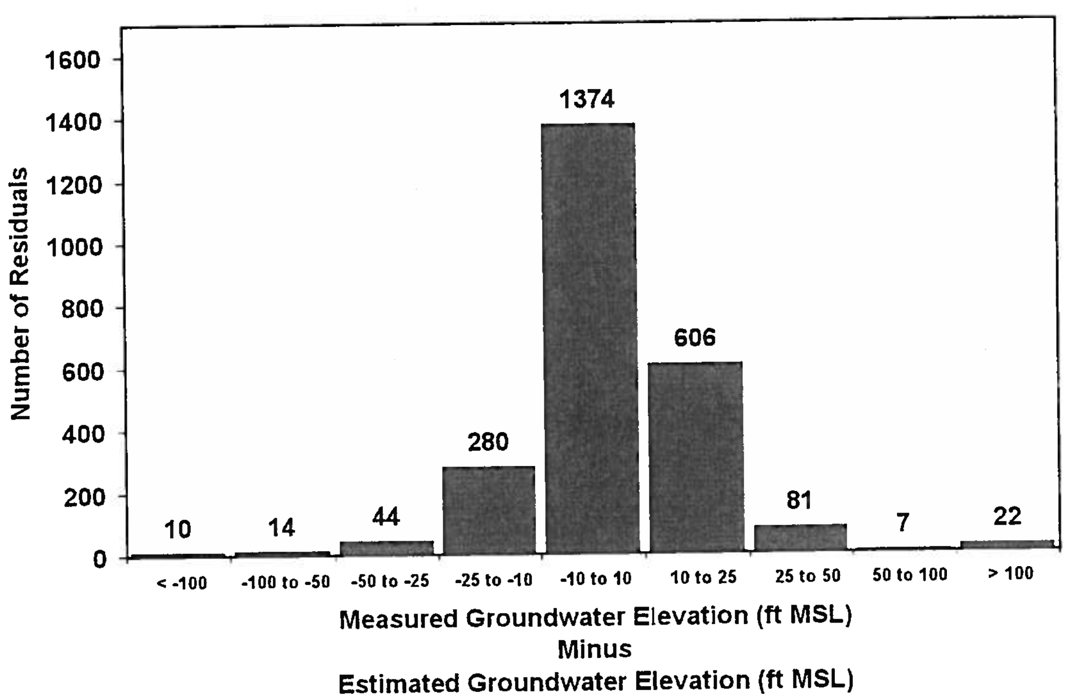


Figure 48. Frequency of Residuals – Structural Geology Model

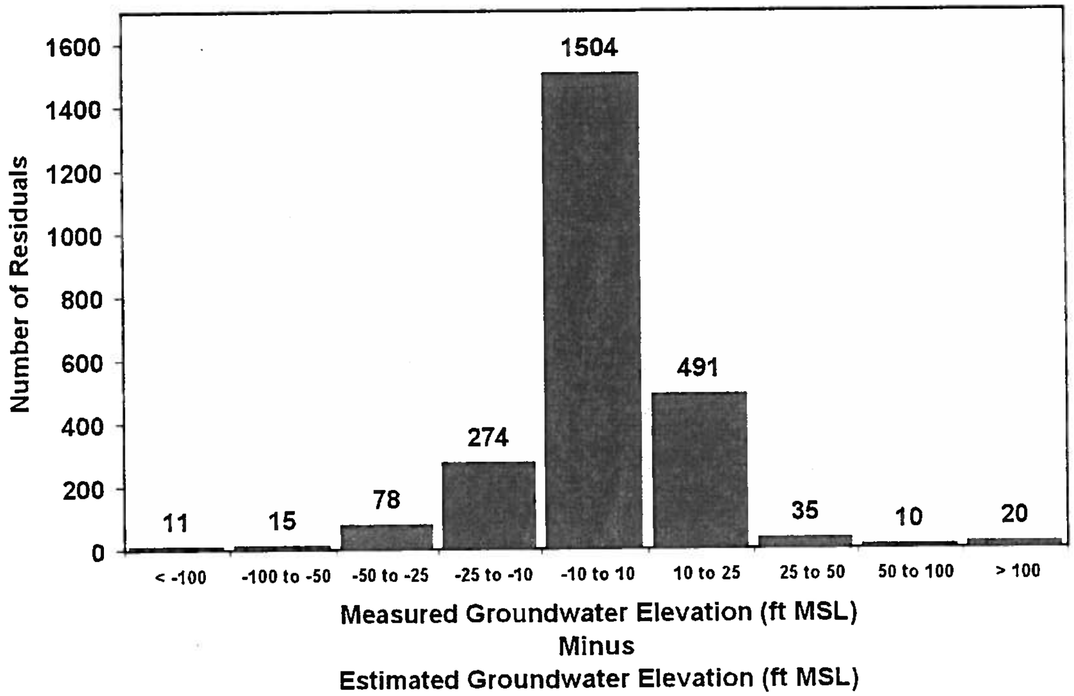


Figure 49. Frequency of Residuals – Isotope Geochemistry Model

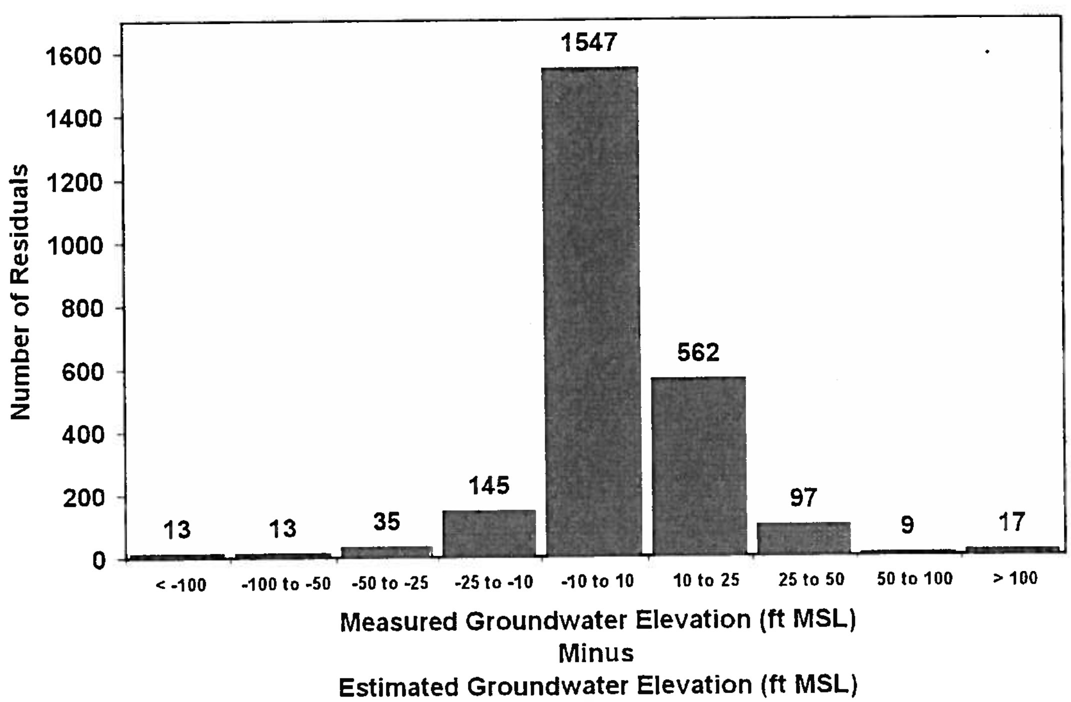


Figure 50. Frequency of Residuals – Hybrid Model

Figures 51, 52, and 53 present plots of model estimated groundwater elevations vs. residuals. Hill and Tiedeman (2007, pg. 101) noted that in this type of plot (ideally) the residuals should be scattered evenly about the zero residual line for the entire range of values on the horizontal axis.

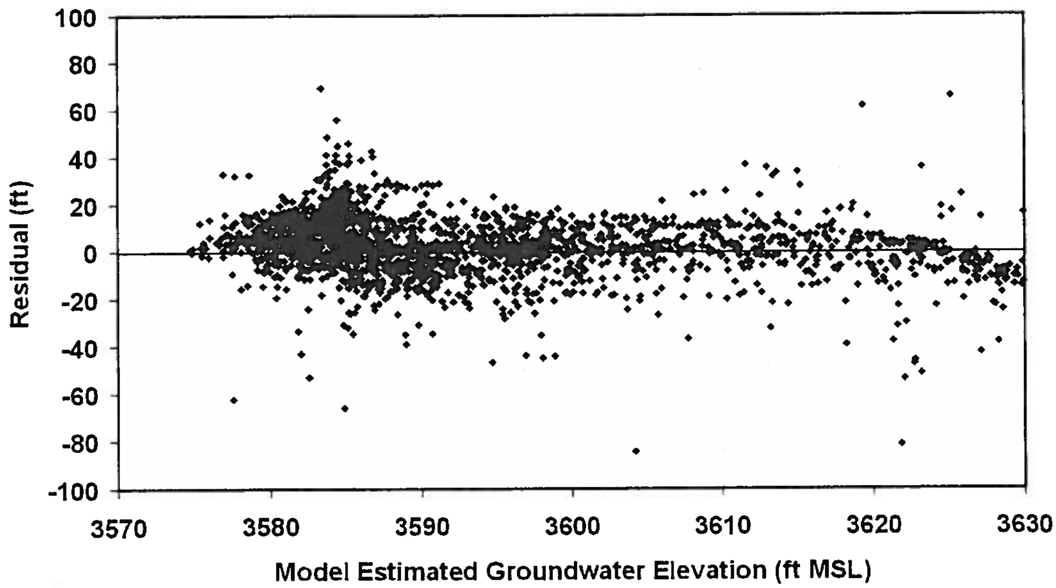


Figure 51. Model Estimated Groundwater Elevation vs. Residual – Structural Geology Model

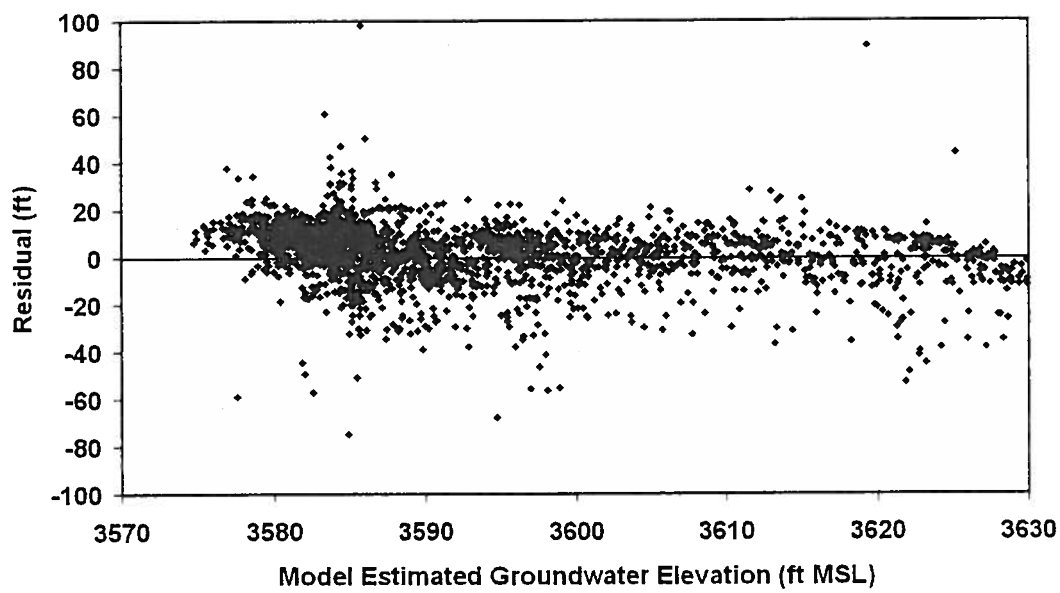


Figure 52. Model Estimated Groundwater Elevation vs. Residual – Isotope Geochemistry Model

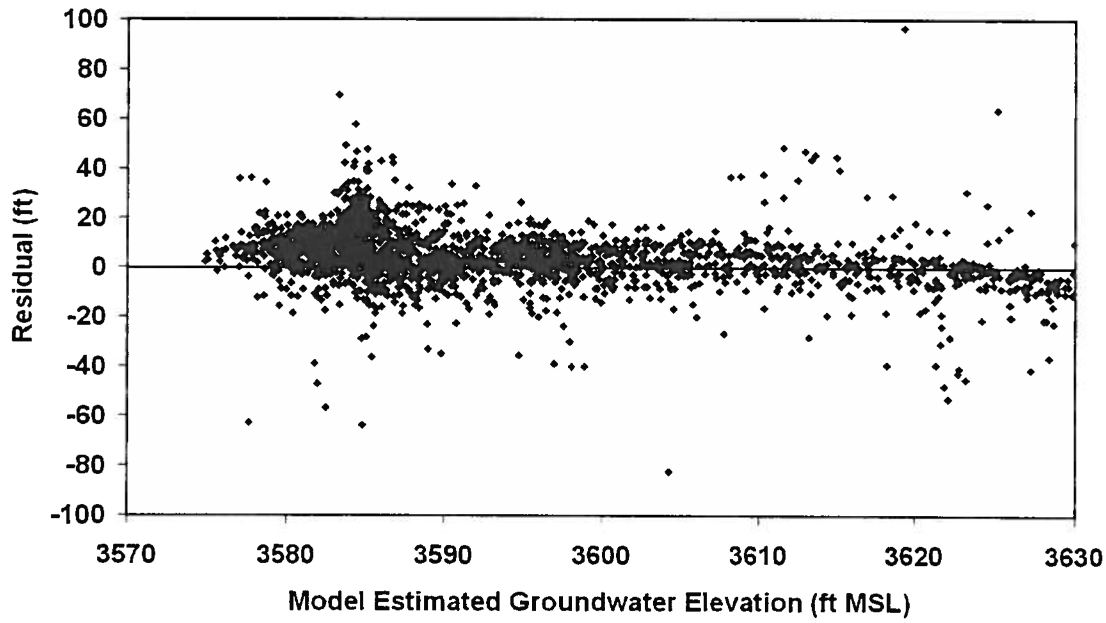


Figure 53. Model Estimated Groundwater Elevation vs. Residual – Hybrid Model

Finally, the calibration fit was also checked spatially and temporally. Spatially, Figures 54, 55, and 56 present plots of model row number vs. model residual, and Figures 57, 58 and 59 present plots of model column number vs. model residual. These plot permit inspection of potential spatial trends in residuals north (low model row number) to south (high model row number) as well as west (low model column number) to east (high model column number).

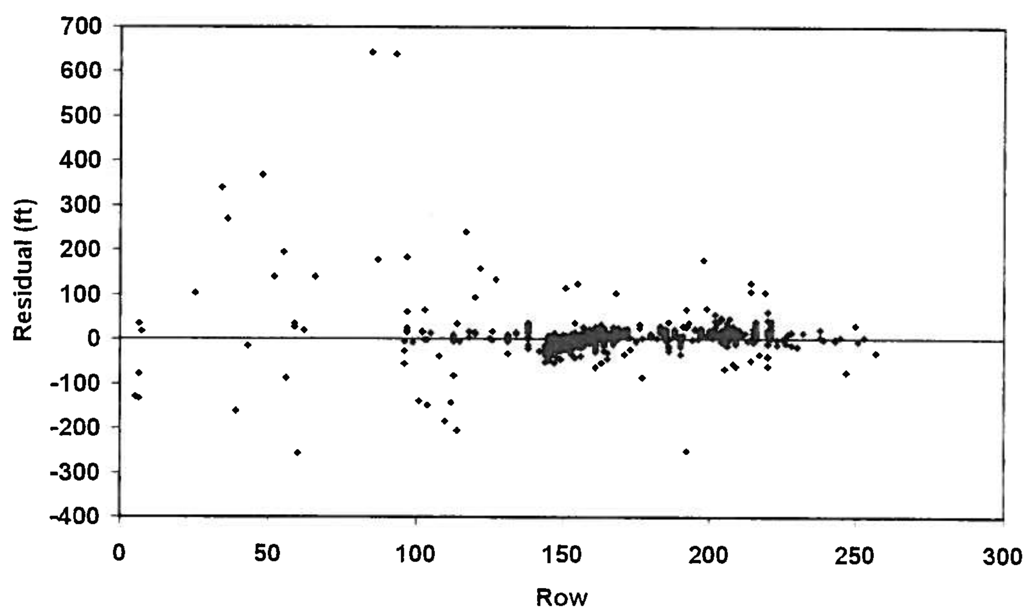


Figure 54. Model Row vs. Residual – Structural Geology Model

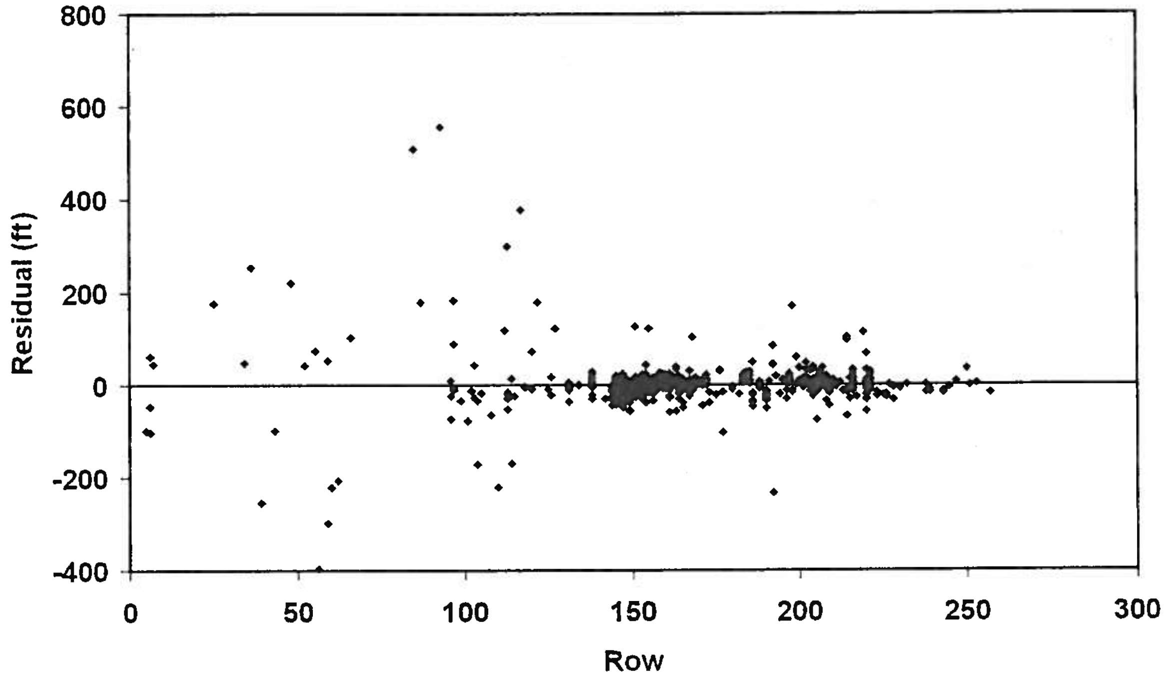


Figure 55. Model Row vs. Residual – Isotope Geochemistry Model

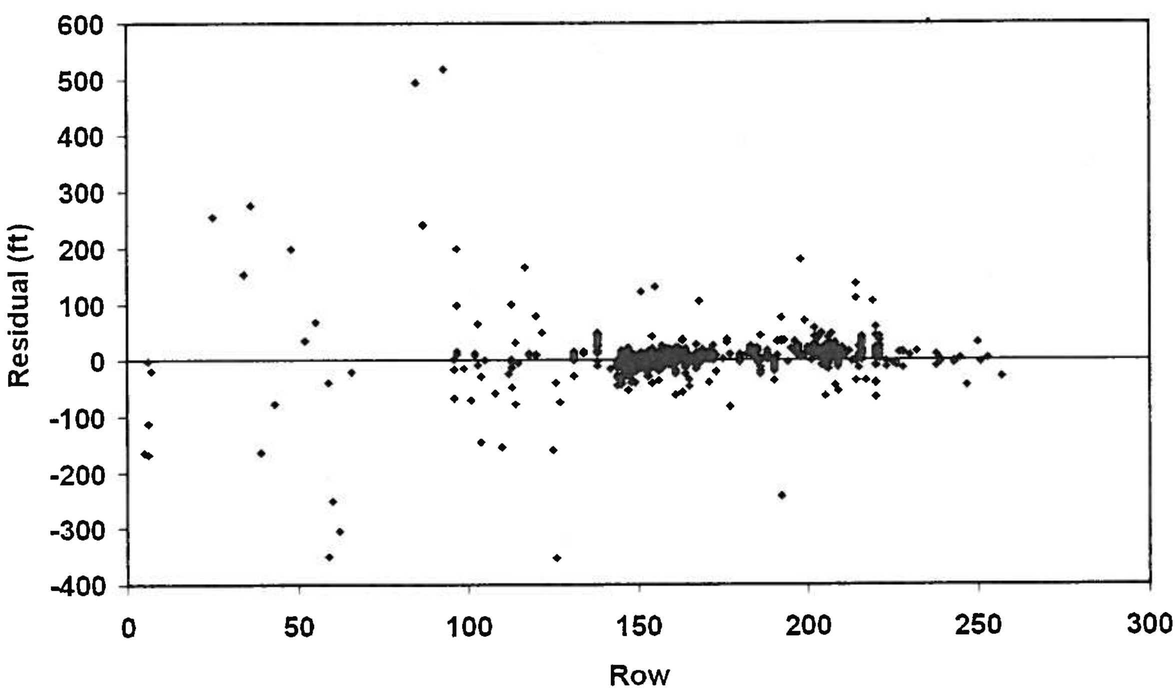


Figure 56. Model Row vs. Residual – Hybrid Model

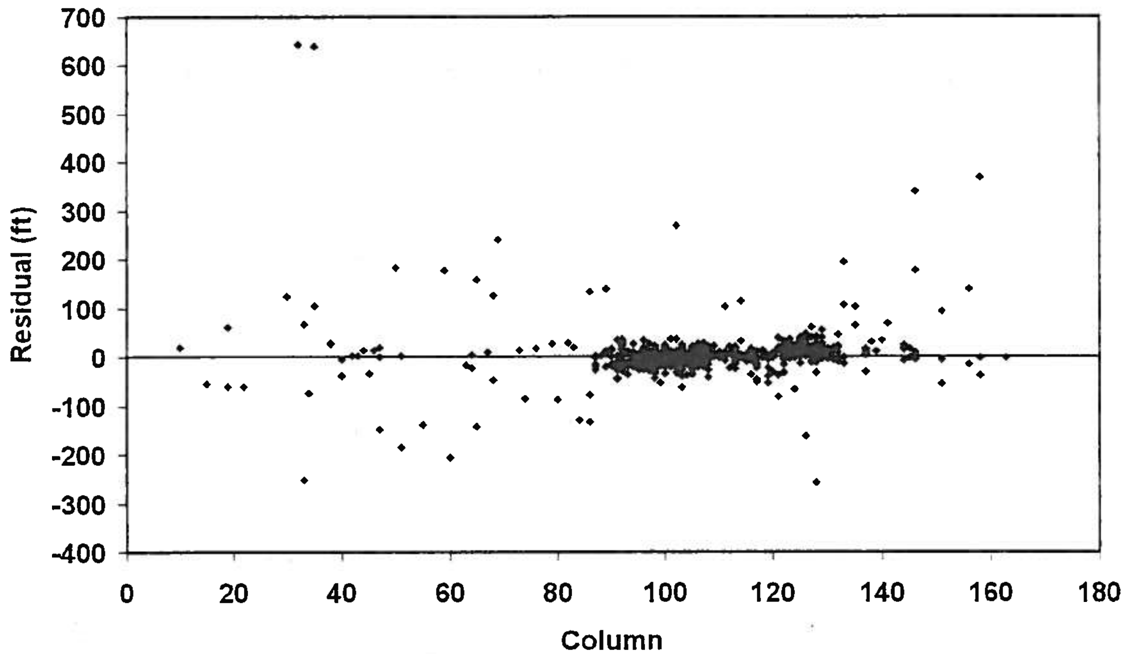


Figure 57. Model Column vs. Residual – Structural Geology Model

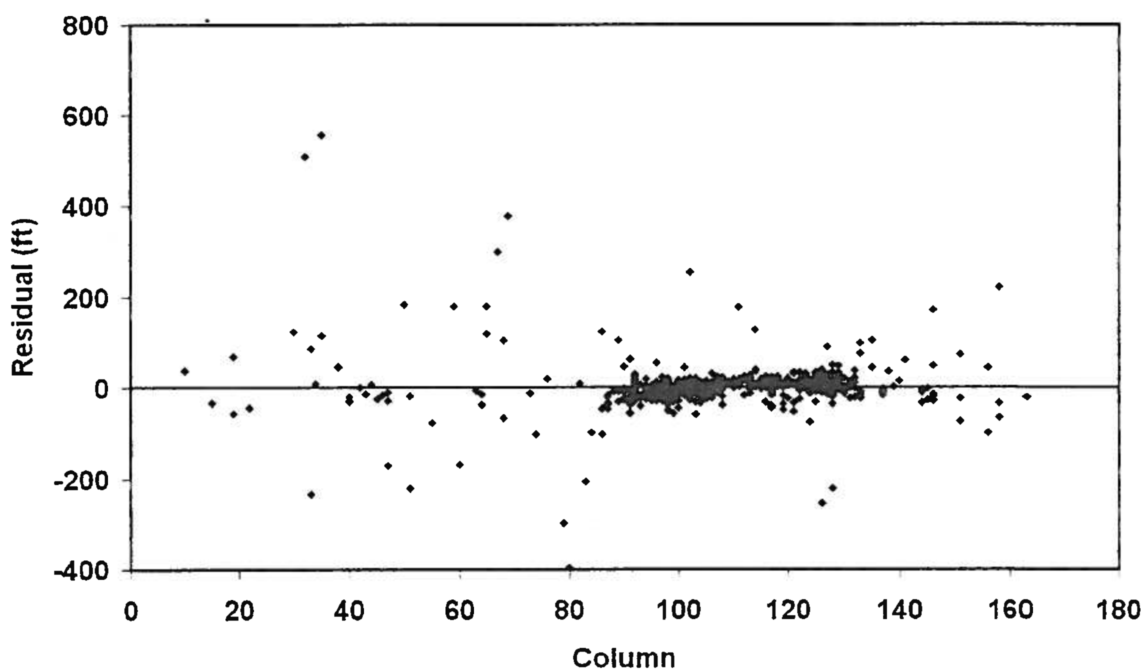


Figure 58. Model Column vs. Residual – Isotope Geochemistry Model

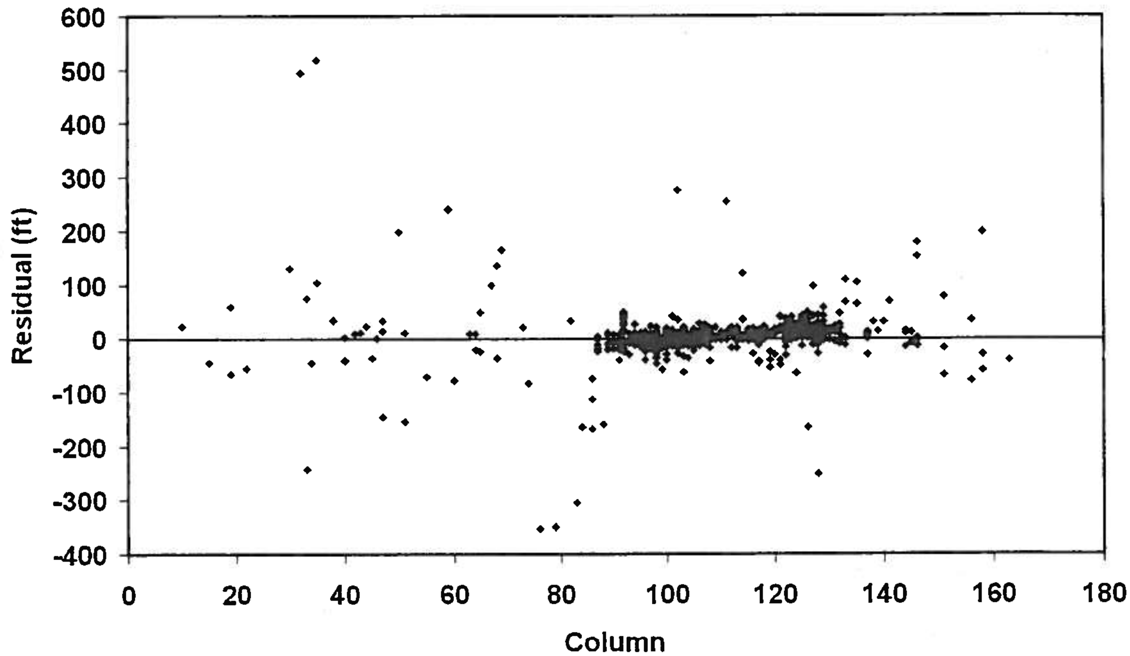


Figure 59. Model Column vs. Residual – Hybrid Model

Temporally, Figures 60, 61, and 62 present plots of year vs. residual. These plots are useful to identify any obvious bias in specific years relative to other years.

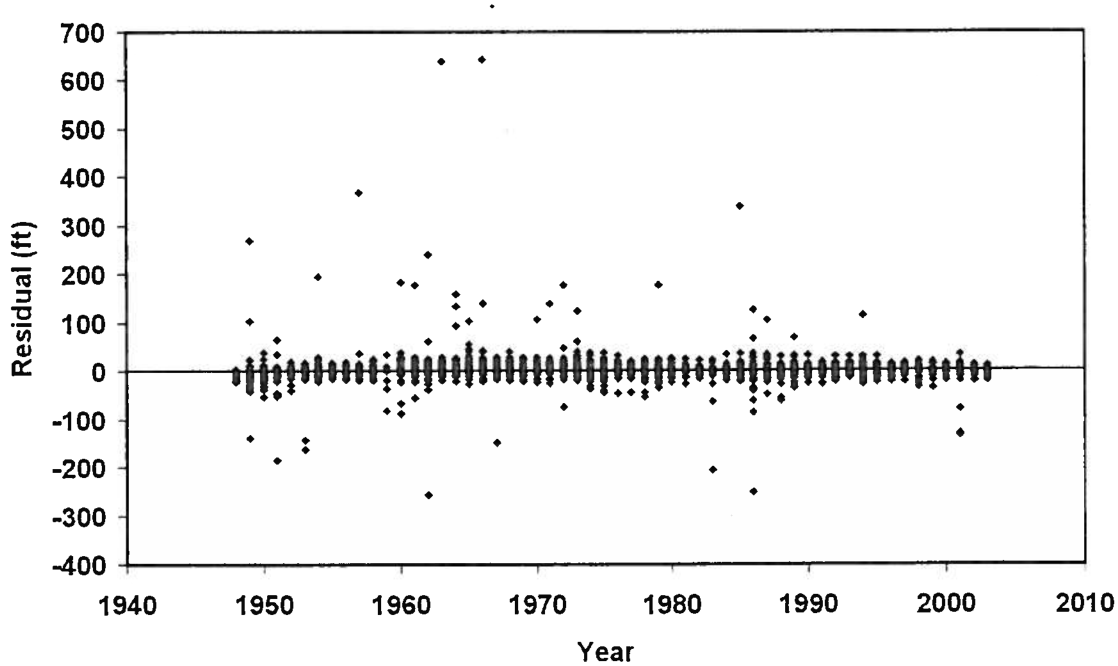


Figure 60. Year vs. Residual – Structural Geology Model

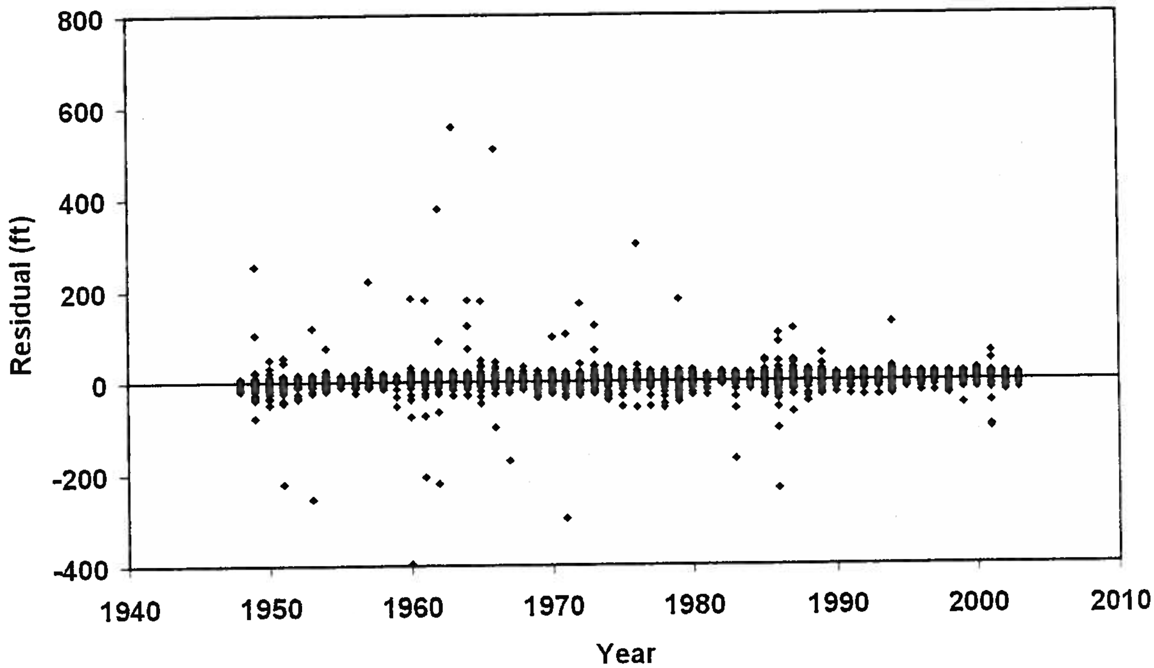


Figure 61. Year vs. Residual – Isotope Geochemistry Model

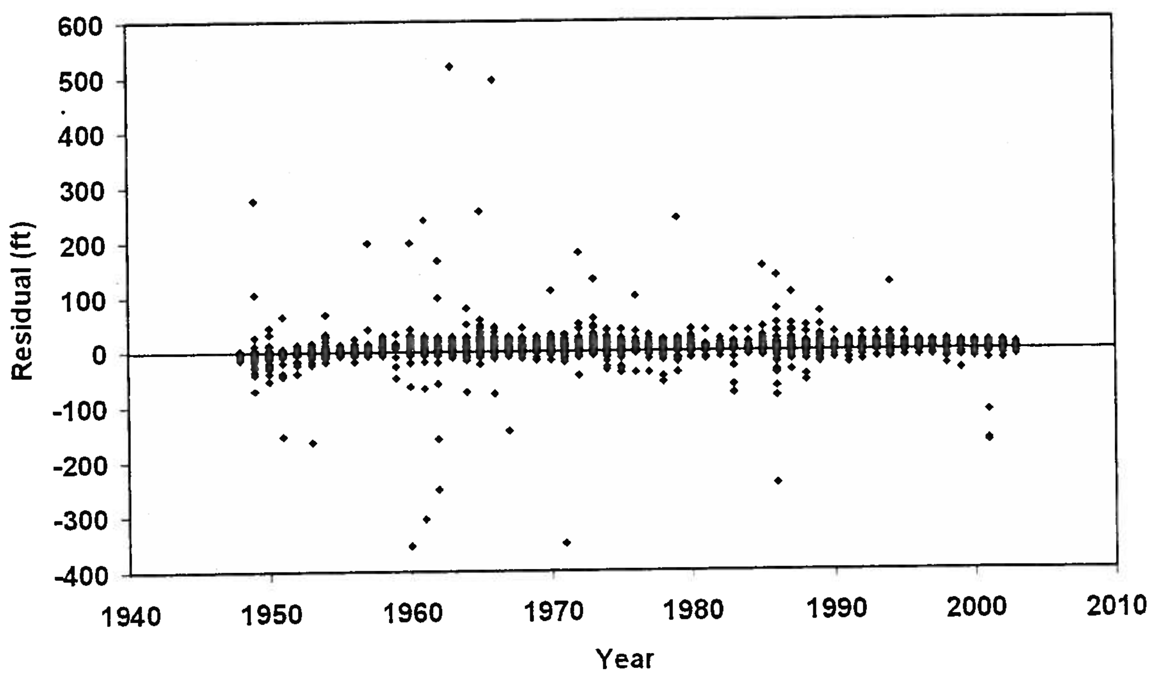


Figure 62. Year vs. Residual – Hybrid Model

7.1.2 Calibration Results for the Dell City Area

The analysis for the entire domain was repeated for the Dell City area as defined by hydraulic conductivity zone 9 of the hybrid model (please see Figure 33). For the Dell City area, a total of 1,675 groundwater elevation measurements were used to compare with model estimated groundwater elevations. Table 29 summarizes calibration statistics.

Table 29. Statistical Summary of the Calibration of All Three Models – Dell City Area

Calibration Statistic (ft)	**Structural Geology Model**	**Isotope Geochemistry Model**	**Hybrid Model**
Minimum Residual (ft)	-62.39	-58.85	-62.62
Maximum Residual (ft)	115.28	126.20	121.97
Average Residual (ft)	-0.73	1.13	1.85
Standard Deviation of Residuals	11.32	11.71	10.20
Range of Measured Groundwater Elevations (ft)	193	193	193
Standard Deviation/Range	5.86E-02	6.07E-02	5.29E-02
Sum of Squared Residuals	2.15E+05	2.32E+05	1.80E+05
Percentage of Residuals Within			
+ 5 ft	29.1	24.4	28.7
+ 10 ft	70.1	56.0	64.0
+ 25 ft	86.1	80.7	86.2

Notable in comparing Table 29 with the statistical summary of the entire model domain in Table 28 is that the minimum residuals are higher and maximum residuals are lower. This means that the highest model errors are outside the Dell City area. The average residuals are closer to zero and the standard deviation values are smaller in the Dell City area than for the entire model domain. The range of measured groundwater elevations is much smaller, as would be expected. The standard deviation divided by the range of measured groundwater elevations is higher, but is still less than 0.10 to 0.15 as suggested by Rumbaugh (2003, pg. 178) to demonstrate an acceptable calibration. Finally, the frequency of residuals summarizes a tighter range as compared with the analysis of the entire model domain due to the closer fit for the area.

Graphical summaries of the match between measured groundwater elevations and model estimated groundwater elevations for each of the three models are presented in Figures 63, 64 and 65. Histograms of the residuals for each of the three models are presented in Figures 66, 67, and 68. As with the analysis of the overall model domain, analysis of these statistical and graphical summaries do not yield any conclusions that one model is superior to the other two.

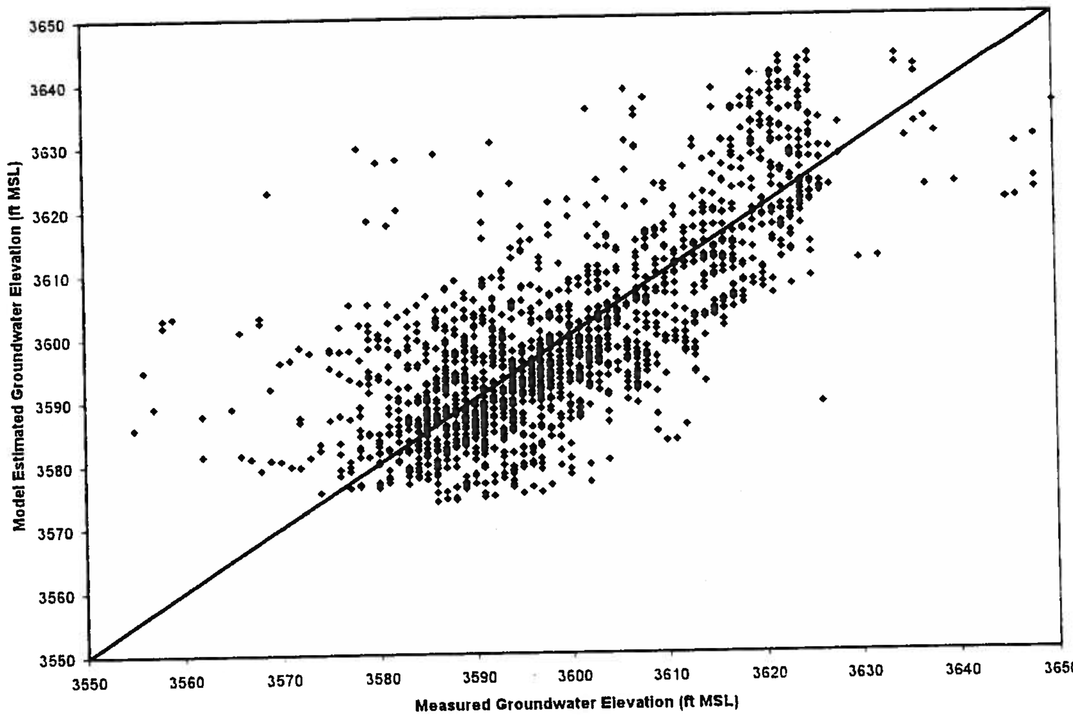


Figure 63. Measured Groundwater Elevation vs. Model Estimated Groundwater Elevations
Dell City Area – Structural Geology Model

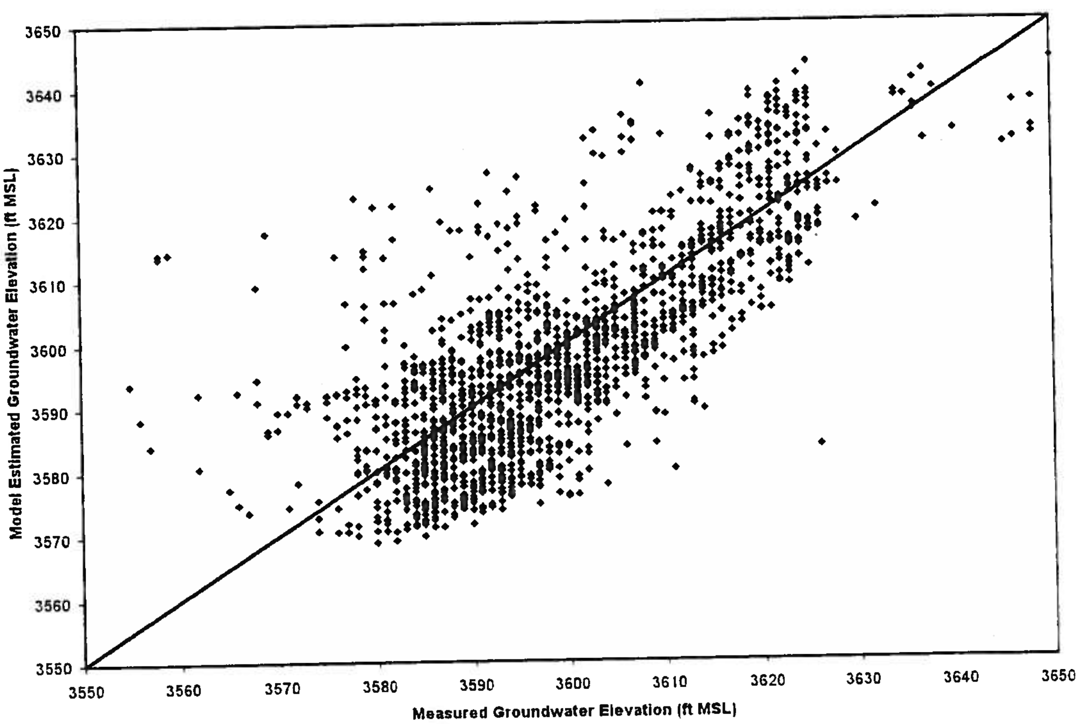


Figure 64. Measured Groundwater Elevation vs. Model Estimated Groundwater Elevations
Dell City Area – Isotope Geochemistry Model

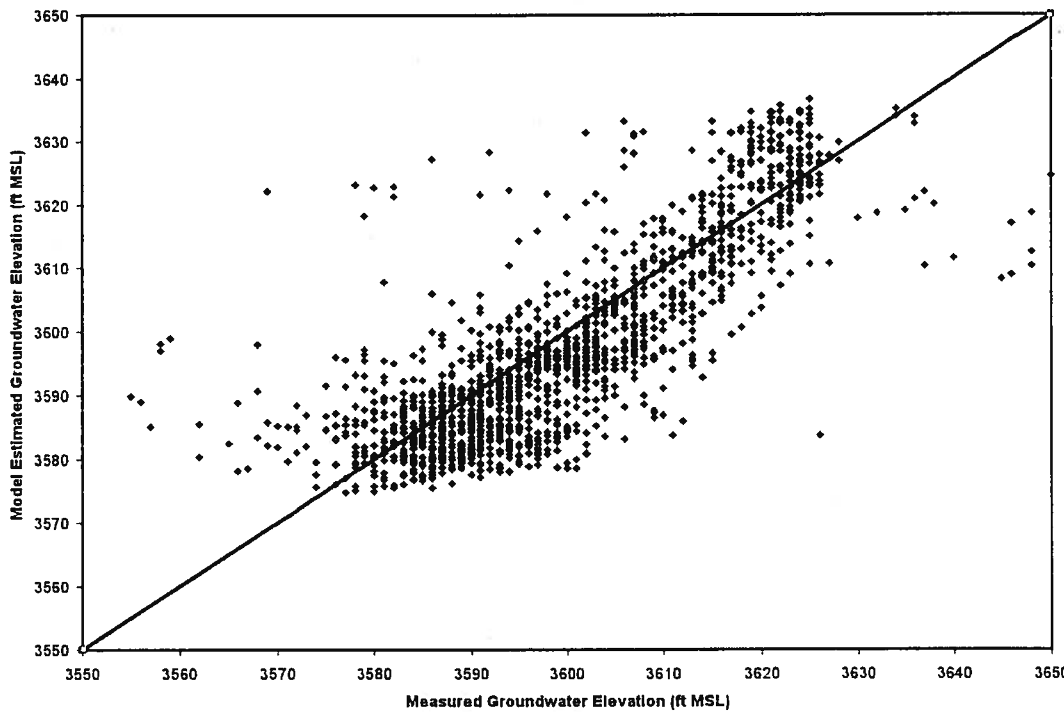


Figure 65. Measured Groundwater Elevation vs. Model Estimated Groundwater Elevations
Dell City Area – Hybrid Model

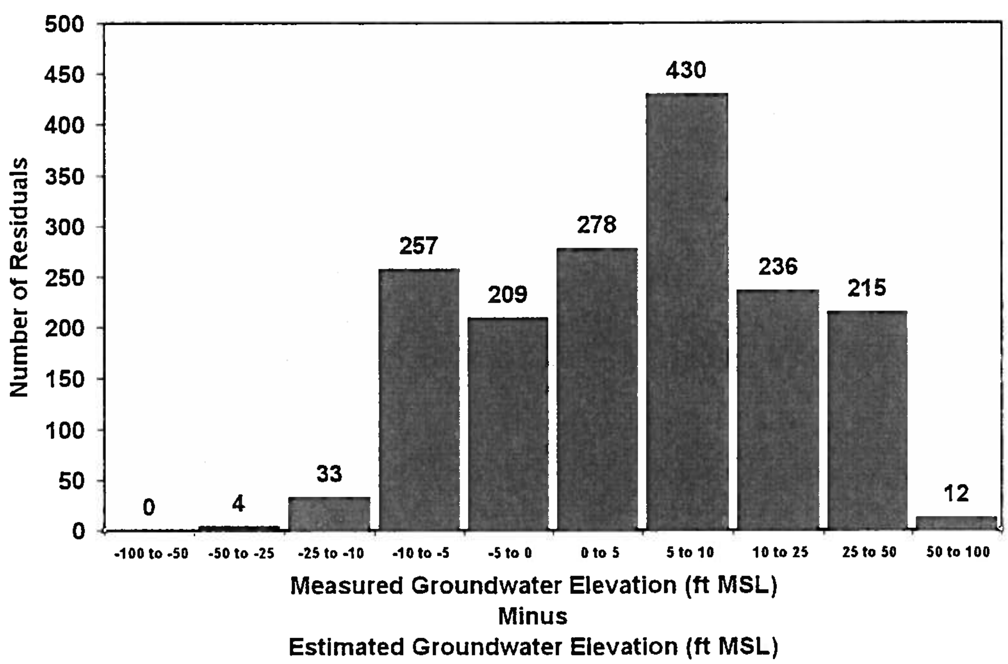


Figure 66. Frequency of Residuals, Dell Area – Structural Geology Model

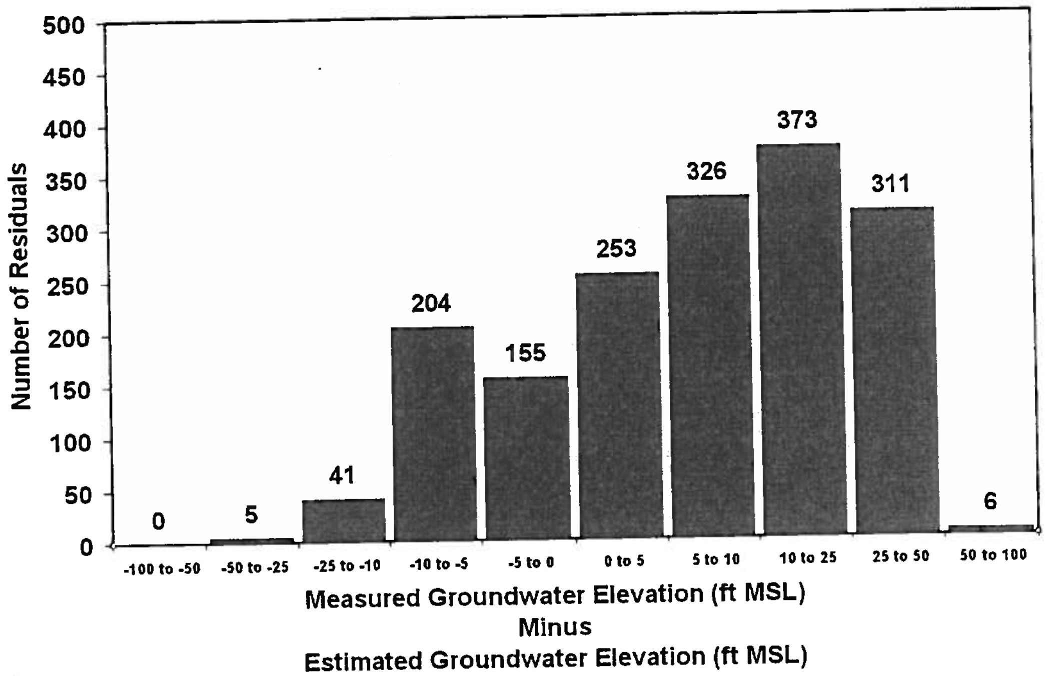


Figure 67. Frequency of Residuals, Dell Area – Isotope Geochemistry Model

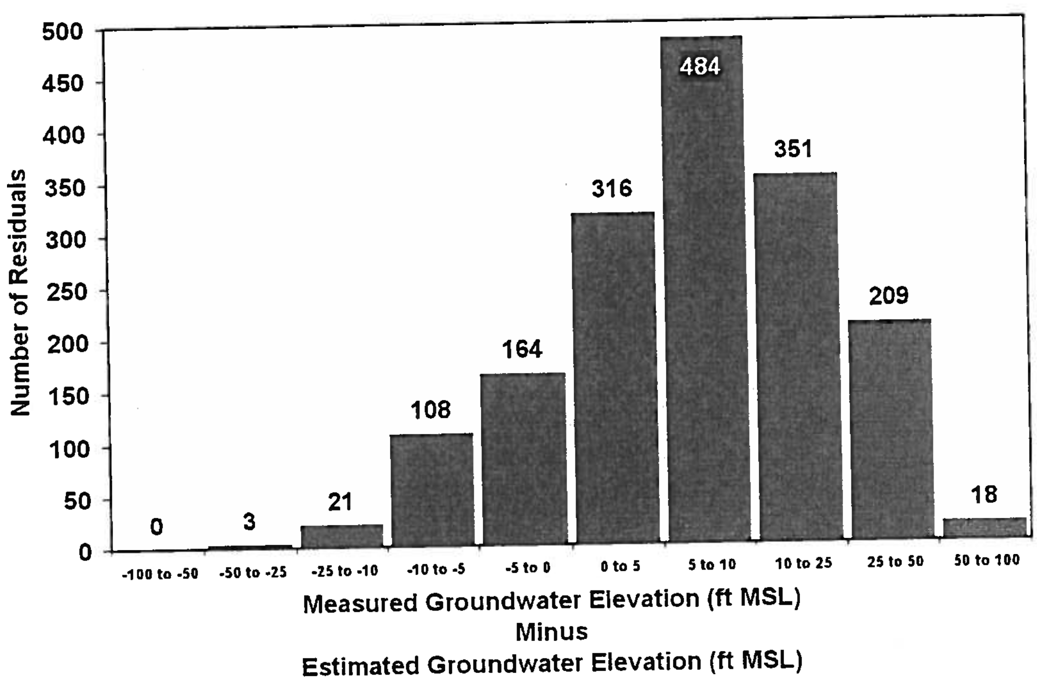


Figure 68. Frequency of Residuals, Dell Area – Hybrid Model

Figures 69, 70 and 71 present plots of model estimated groundwater elevations vs. residuals for the Dell City area. Hill and Tiedeman (2007, pg. 101) noted that in this type of plot (ideally) the residuals should be scattered evenly about the zero residual line for the entire range of values on the horizontal axis. The y-axis is limited to +60 which results in the removal of two outliers to permit more effective visualization of the spread of residuals.

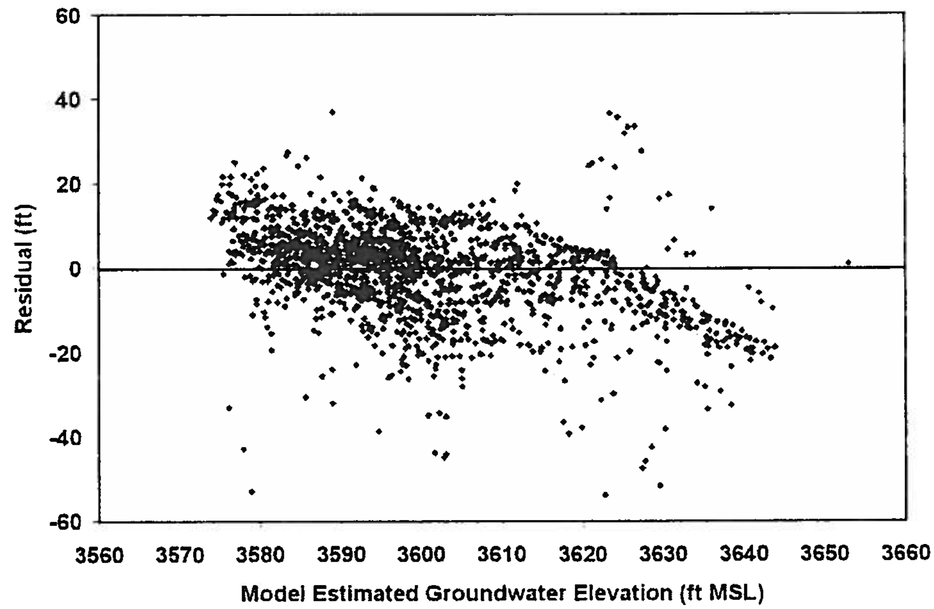


Figure 69. Model Estimated Groundwater Elevation vs. Residual, Dell City Area Structural Geology Model

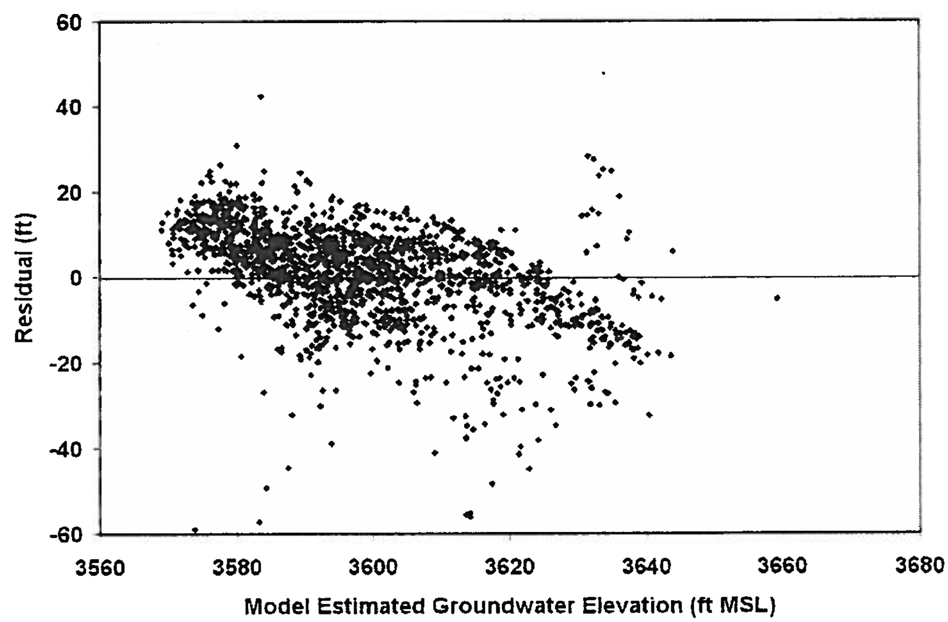


Figure 70. Model Estimated Groundwater Elevation vs. Residual, Dell City Area Isotope Geochemistry Model

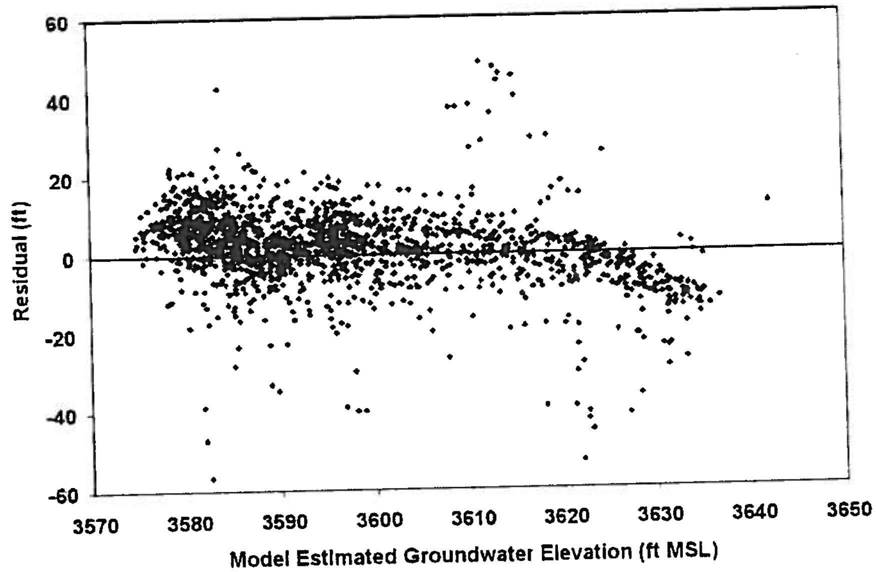


Figure 71. Model Estimated Groundwater Elevation vs. Residual, Dell City Area
Hybrid Model

Finally, the calibration fit in the Dell City area was also checked spatially and temporally. Spatially, Figures 71, 72, and 73 present plots of model row number vs. model residual, and Figures 74, 75 and 76 present plots of model column number vs. model residual.

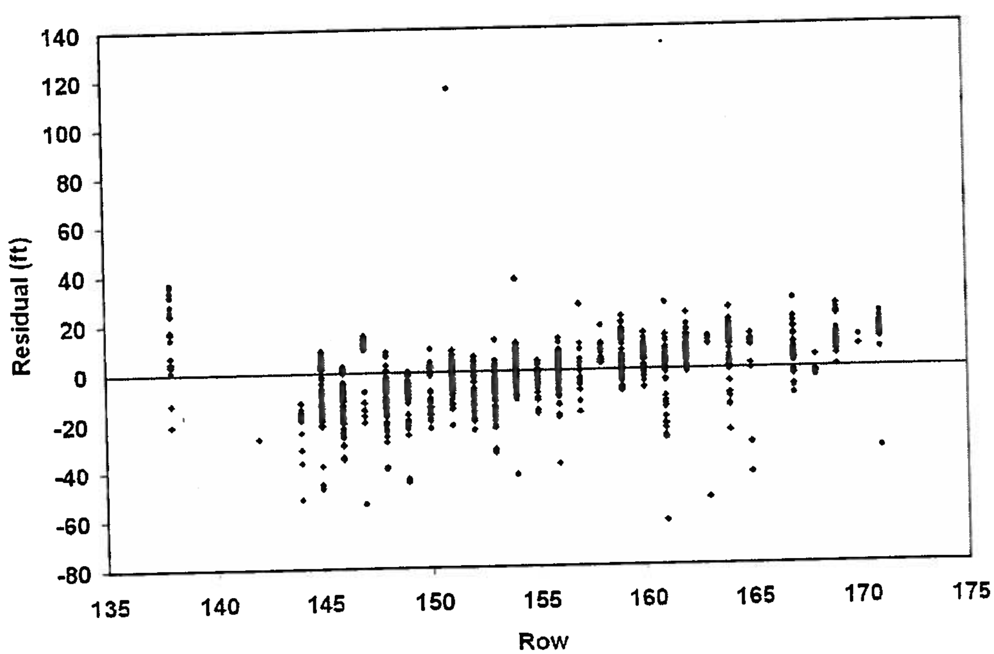


Figure 72. Model Row vs. Residual, Dell City Area – Structural Geology Model

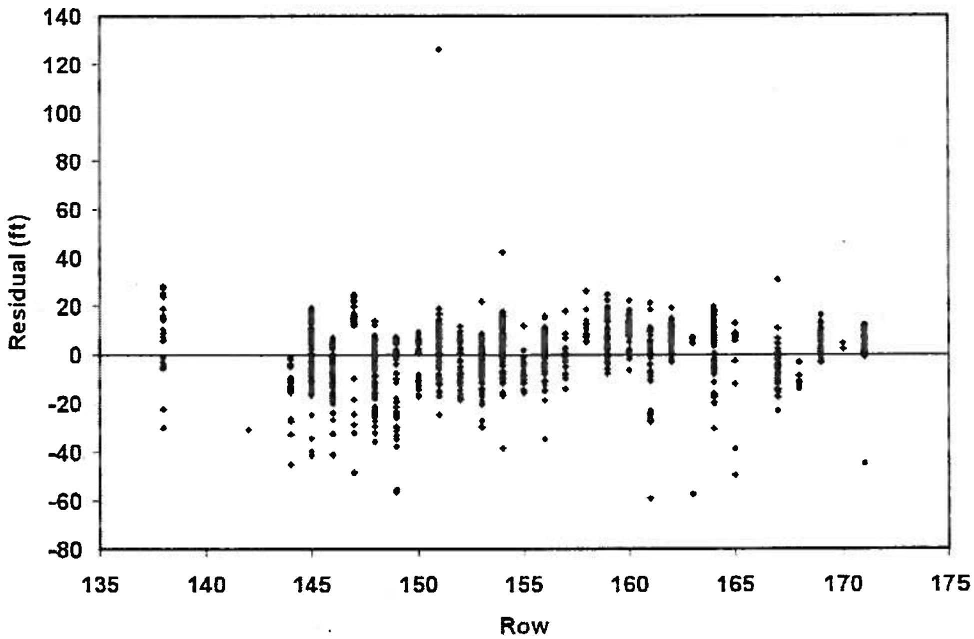


Figure 73. Model Row vs. Residual, Dell City Area – Isotope Geochemistry Model

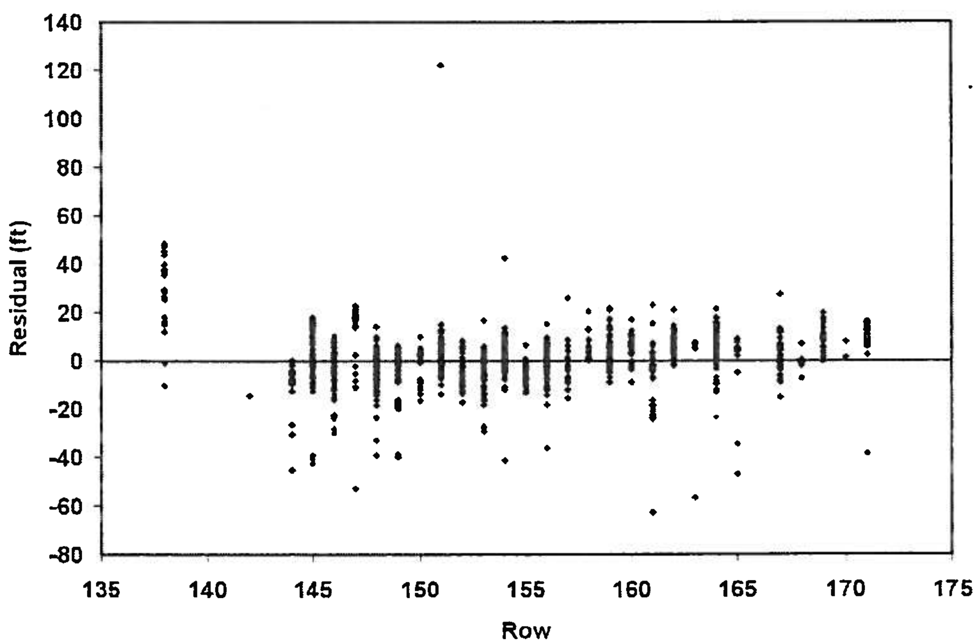


Figure 74. Model Row vs. Residual, Dell City Area – Hybrid Model

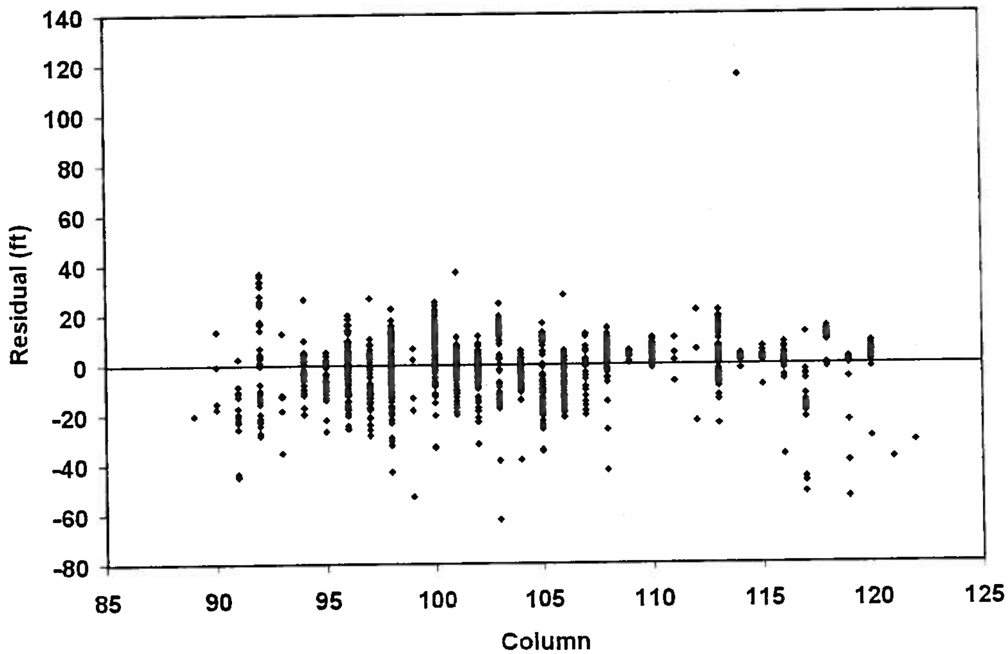


Figure 75. Model Column vs. Residual, Dell City Area – Structural Geology Model

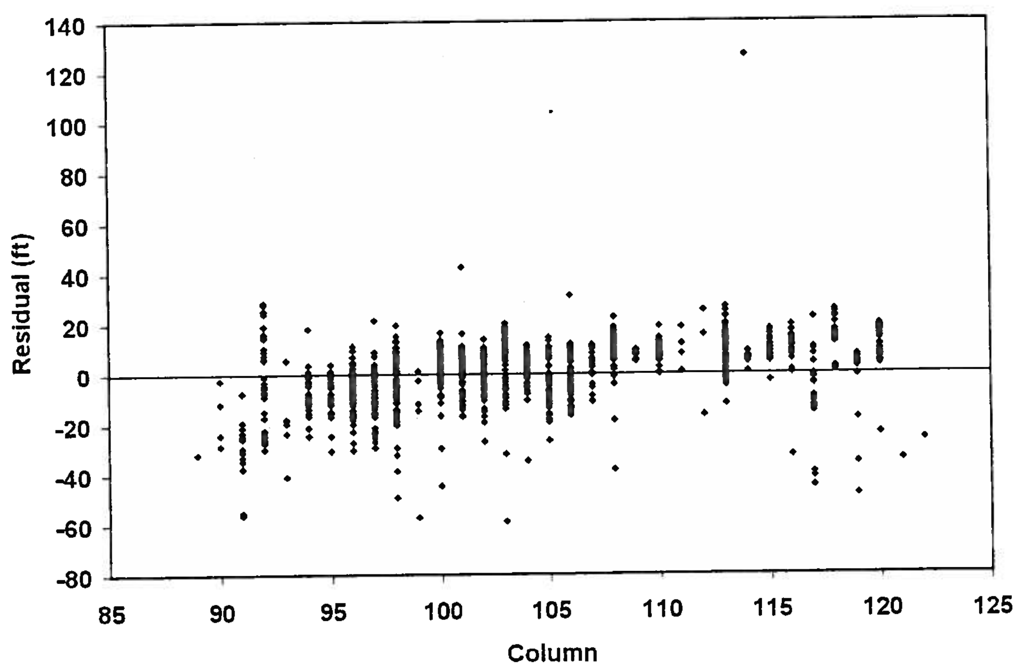


Figure 76. Model Column vs. Residual, Dell City Area – Isotope Geochemistry Model

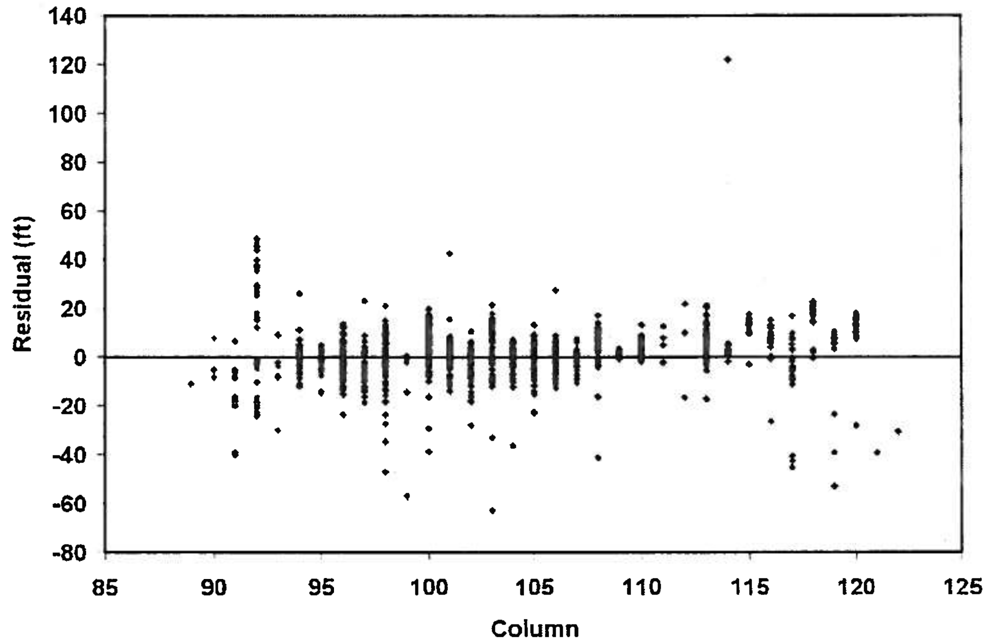


Figure 77. Model Column vs. Residual, Dell City Area – Hybrid Model

Temporally, Figures 78, 79, and 80 present plots of year vs. residual. These plots are useful to identify any obvious bias in specific years relative to other years.

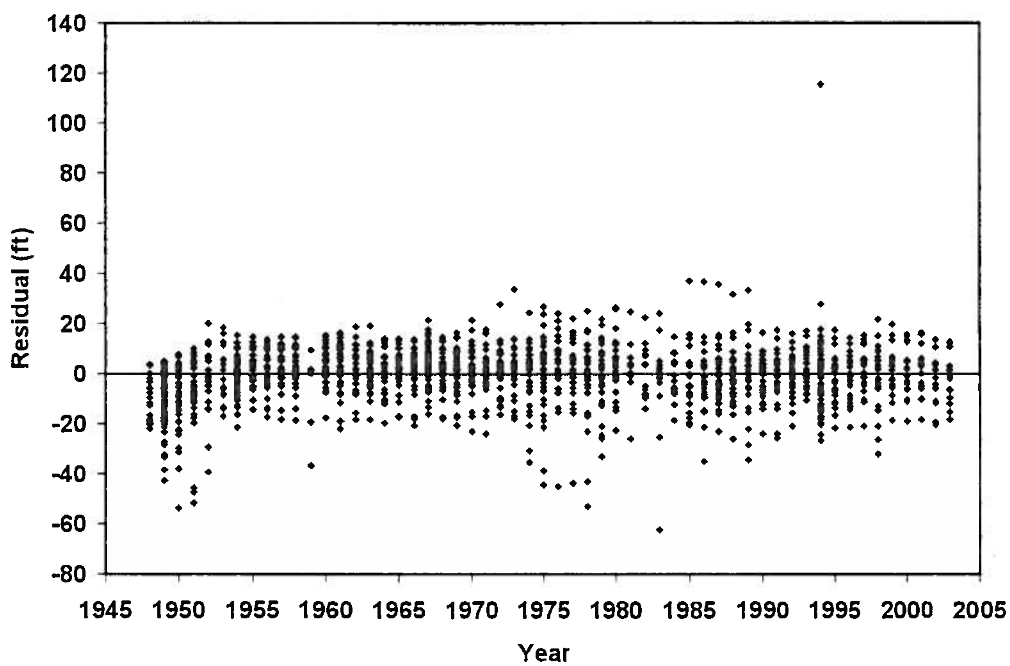


Figure 78. Year vs. Residual, Dell City Area – Structural Geology Model

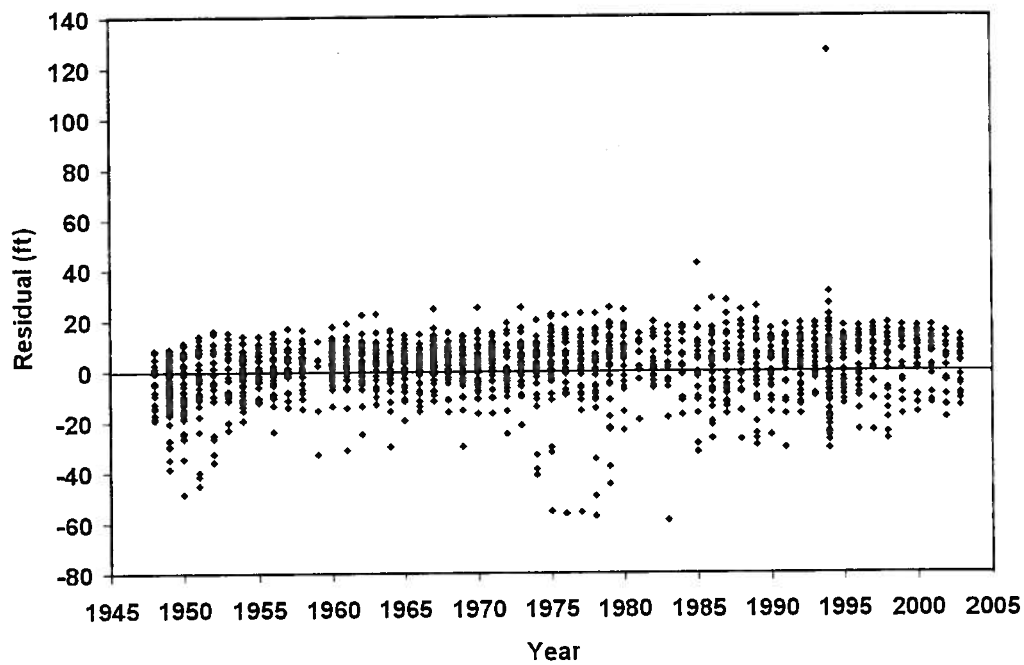


Figure 79. Year vs. Residual, Dell City Area – Isotope Geochemistry Model

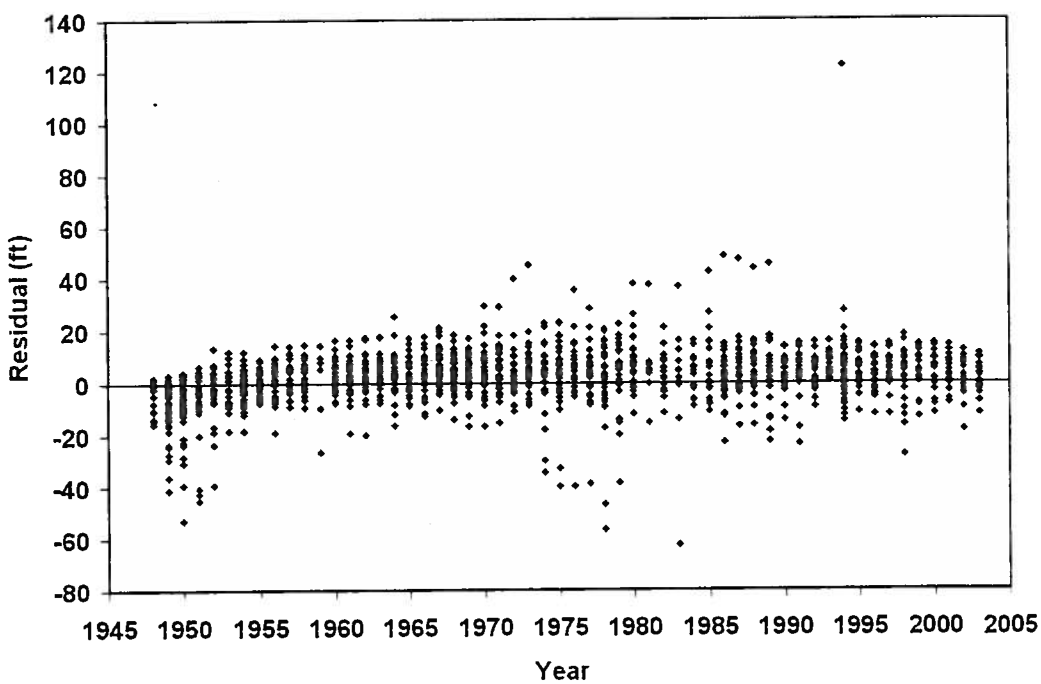


Figure 80. Year vs. Residual, Dell City Area – Hybrid Model

7.1.3 Discussion of Residual Analysis

The residual analysis suggests that the models are all well calibrated. However, it should be noted that the residuals in both the overall domain analysis and particularly in the Dell City area are not normally distributed. This is evident from the residual means being greater than zero, the skewed distribution shown in the histograms, and the apparent slope present in the plots of model estimated groundwater elevations vs. residuals. Standard statistical tests were applied to determine whether the residuals are normally distributed. Based on many of these tests, it was not possible to conclude that the residuals were normally distributed to a reasonable degree of significance.

Lack of a normal distribution would prevent the use of certain results from the parameter estimation effort (e.g. confidence limits on parameter estimates). The lack of a normal distribution also limits the use of statistics such as standard deviation to be used in any quantitative analysis beyond what was presented.

It should be noted that no effort was made to "weight" the measured groundwater elevations in the analysis. Hill and Tiedeman (2007) discuss the topic of weighted residuals at some length. The parameter estimation software used in this effort, PEST, allows for the weighting of "observations" (in this case groundwater elevations). However, the weighting of observations when all observations are groundwater elevations is simply a method to reduce the importance of measured data in the parameter estimation process. In an attempt to treat every measured point equally, all observations were weighted equally. Clearly, if observations were weighted, the residuals could be "forced" to be normally distributed.

If a single model had been developed, and parameter confidence limits were an objective of the analysis, weighting would be been implemented. The real objective was to test three separate conceptual models by developing and calibrating three numerical models. Inherent in the development of the three numerical models are expression of parameter ranges and parameter sensitivity that utilizes all measured data equally.

7.1.4 Hydrograph Comparison

The final comparison between measured groundwater elevations and model estimated groundwater elevations is through inspection of hydrographs of 46 wells. As previously presented in Tables 26 and 27, many of the wells used for calibration had one to a few readings. However, 46 wells from this group were chosen because they had over 20 measurements over several years. A few had nearly complete records (1948 to 2002). The locations of these 46 wells are shown in Figure 81, and data associated with them are summarized in Table 30a (New Mexico wells) and 30b (Texas wells). The hydrographs of all 46 wells are presented in Appendix C (a copy of the map and tabular summary is repeated in the Appendix C).

The locations of three of the wells are shown in Figure 82, and their hydrographs are shown in Figures 83 to 85. These wells include a well located north of the irrigated area in New Mexico (25S.18E.21.233), a well with a long record in Dell City (48-07-501), and a well in the Diablo Farms area that pumps from the Capitan Reef (47-17-302).

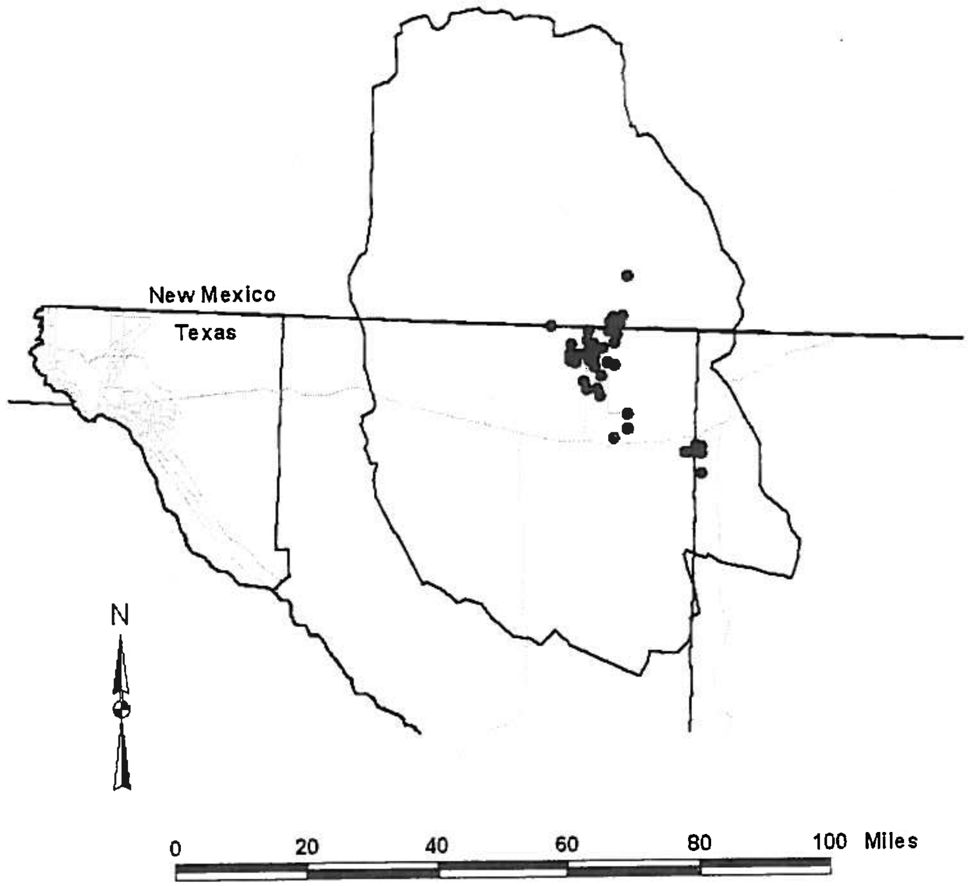


Figure 81. Location of Wells used in Hydrograph Analysis Presented in Appendix C

Table 30a. Summary of Wells with Hydrographs of Actual Groundwater Elevation and Model Estimated Groundwater Elevation Hydrographs (New Mexico Wells)

Well Number	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (ft MSL)	Lowest Groundwater Elevation (ft MSL)	Year of Earliest Measurement	Year of Latest Measurement
25S.18E.21.233	131	128	30	3593	3617	1958	1992
26S.18E.21.313	145	120	44	3598	3626	1955	1999
26S.18E.30.122	144	117	22	3532	3557	1955	1994
26S.18E.30.321	145	115	24	3557	3582	1949	1999
26S.18E.32.122	147	118	26	3562	3588	1955	1984

Table 30b. Summary of Wells with Hydrographs of Actual Groundwater Elevation and Model Estimated Groundwater Elevation Hydrographs (Texas Wells)

Well Number	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (ft MSL)	Lowest Groundwater Elevation (ft MSL)	Year of Earliest Measurement	Year of Latest Measurement
47-17-202	206	122	45	3564	3612	1953	2002
47-17-203	207	126	33	3583	3614	1957	1995
47-17-205	206	123	43	3579	3625	1953	1999
47-17-206	206	126	41	3585	3613	1959	2002
47-17-302	209	128	38	3569	3607	1957	2002
47-17-304	206	129	32	3591	3608	1964	2000
47-17-317	205	127	27	3571	3607	1964	1995
47-17-601	216	125	30	3591	3627	1958	1994
48-06-201	138	92	23	3603	3660	1953	1988
48-07-102	148	97	25	3577	3602	1963	2002
48-07-203	145	106	50	3580	3625	1947	1995
48-07-206	146	105	43	3566	3634	1947	2002
48-07-207	149	104	41	3578	3605	1959	2002
48-07-214	151	106	26	3579	3603	1966	1993
48-07-301	148	113	45	3581	3625	1947	1995
48-07-304	154	113	42	3574	3614	1953	2002
48-07-402	155	96	29	3588	3619	1947	1973
48-07-403	151	100	25	3584	3624	1947	1974
48-07-405	153	98	47	3577	3624	1947	2002
48-07-414	154	94	25	3581	3604	1963	1994
48-07-418	151	95	33	3579	3603	1966	2002
48-07-501	156	101	51	3578	3626	1947	2002
48-07-502	156	104	55	3574	3621	1947	2002
48-07-504	154	101	36	3582	3626	1947	1984
48-07-505	156	101	26	3579	3616	1953	1992
48-07-516	153	102	37	3566	3601	1966	2002
48-07-606	154	108	55	3576	3627	1947	2002
48-07-607	160	108	40	3578	3606	1959	2002
48-07-708	164	96	29	3562	3599	1966	2002
48-07-801	159	102	37	3571	3621	1947	2002
48-07-803	162	98	47	3585	3625	1952	2002
48-07-901	162	110	40	3577	3602	1958	2002
48-07-904	164	103	42	3584	3617	1949	2002
48-08-102	151	116	31	3582	3601	1966	1998
48-15-201	169	100	37	3582	3607	1959	1999
48-15-203	167	96	36	3568	3617	1953	1995
48-15-301	171	100	41	3586	3612	1959	2002
48-15-302	172	105	25	3581	3604	1963	1993
48-15-902	190	98	32	3549	3590	1959	2002
48-16-402	183	107	25	3593	3617	1959	1993
48-16-702	188	105	25	3586	3608	1959	1994

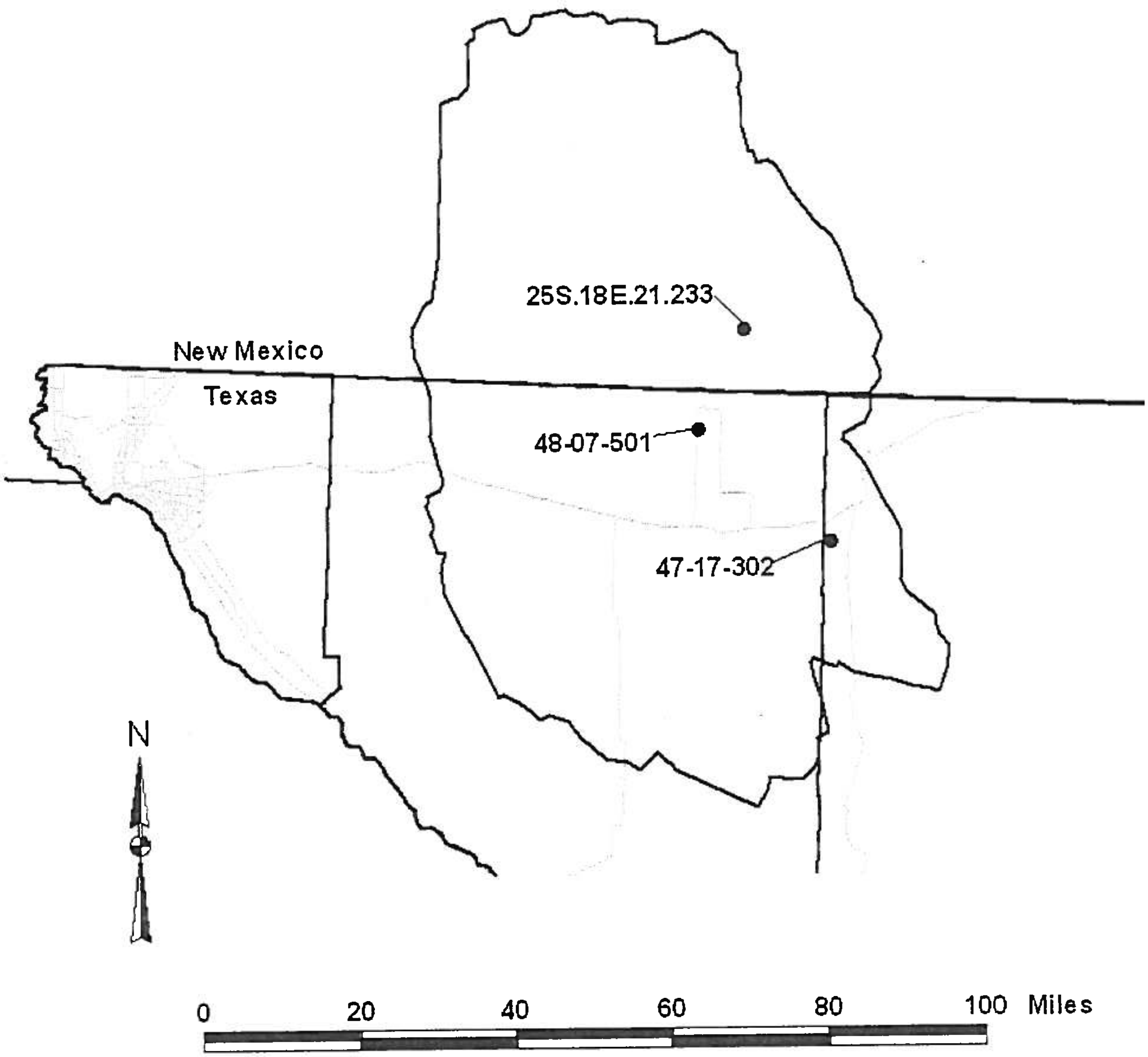
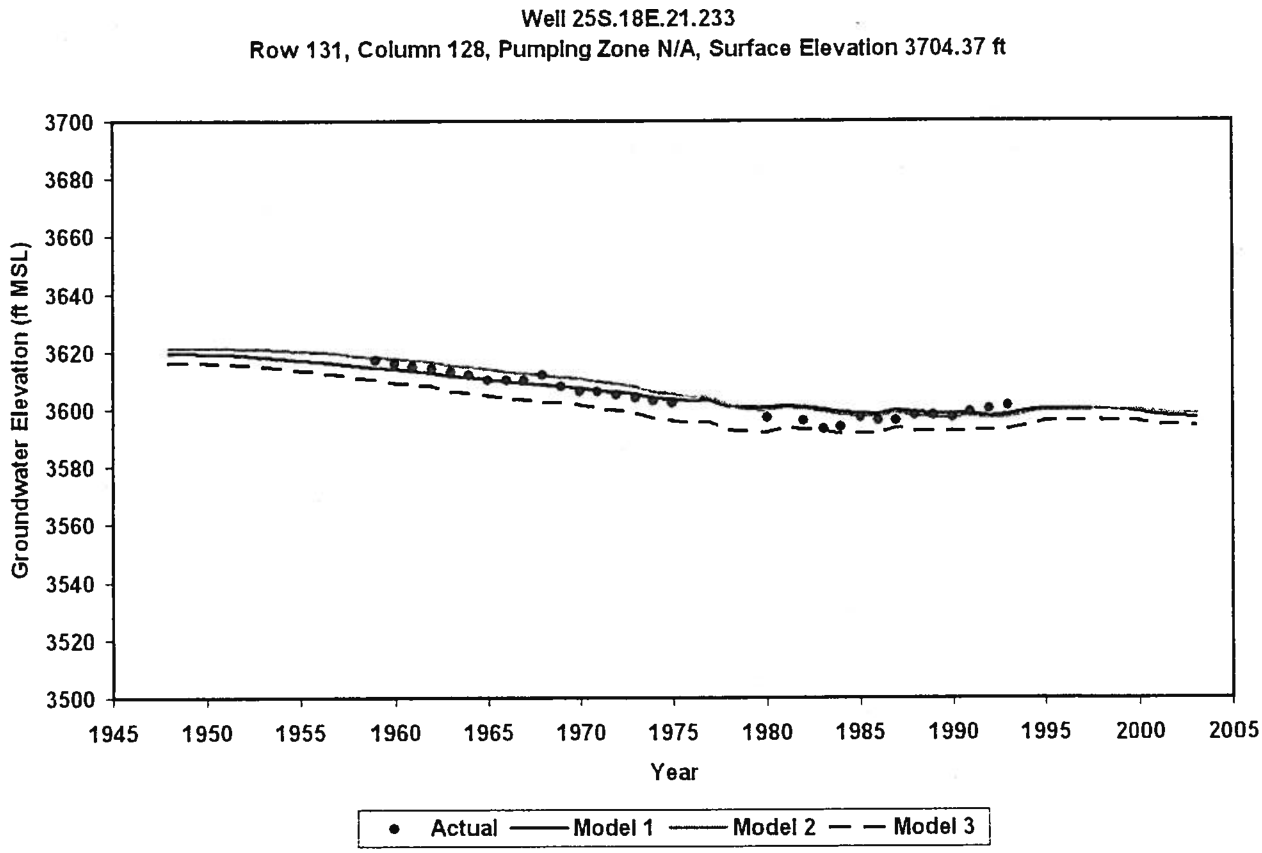
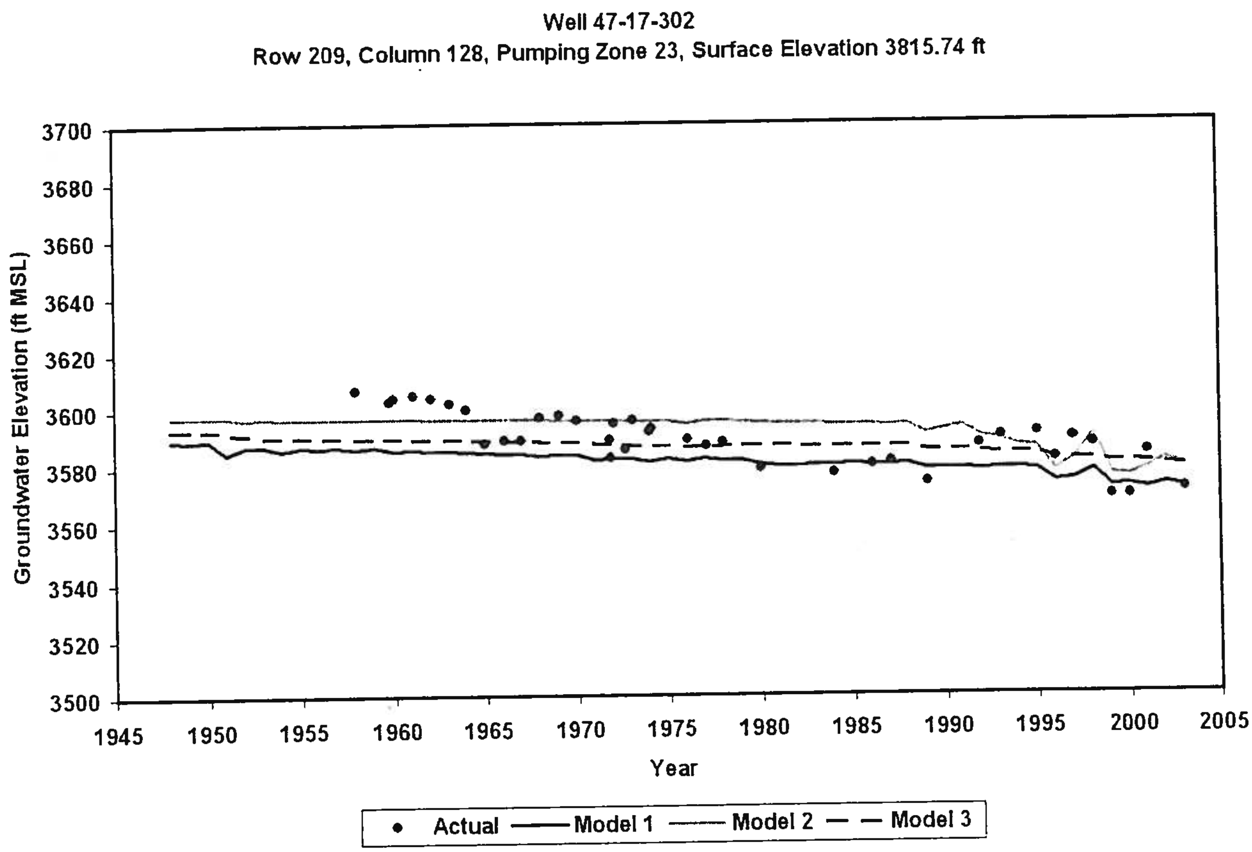


Figure 82. Location of Three Wells with Hydrographs (Figures 83 to 85)



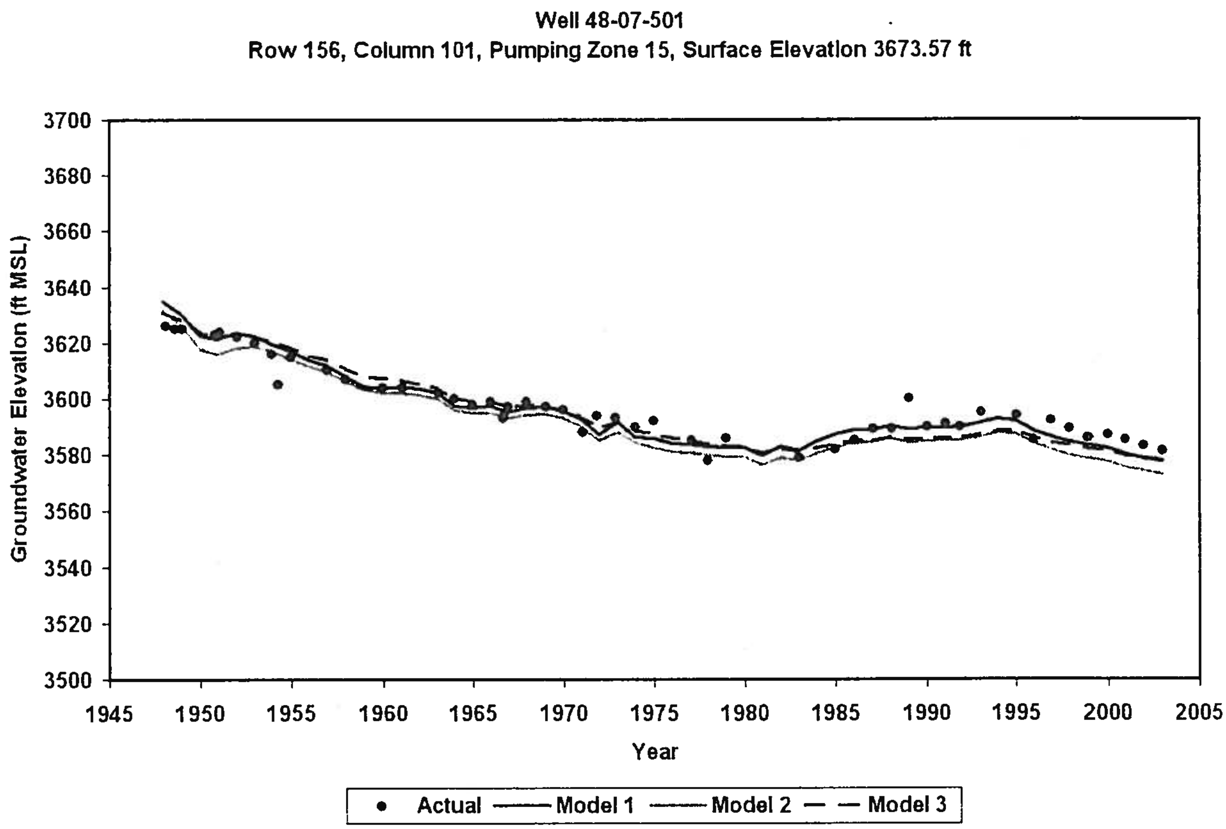
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

Figure 83. Hydrograph of Well 25S.18E.21.233



Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

Figure 84. Hydrograph of Well 47-17-302



Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

Figure 85. Hydrograph of Well 47-07-501

7.2 Analysis of Irrigated Acreage

As developed previously in Section 6.3.4 regarding estimates of groundwater pumping, the estimates of Groeneveld and Baugh (2002) were used as initial estimates for irrigated acreage. These acreage estimates (for each of the 25 pumping zones) were multiplied with estimates of duty to develop estimates of consumptive or net pumping used in the model. During calibration, duties and acreages were adjusted, and Section 6.3.4 summarized the resulting consumptive or net pumping estimates. The adjustments of duty and acreage were not tightly constrained as a check of the model conceptualization and calibration. If the constraints on duty and acreage had been severe, it is possible that a calibrated model would have been developed, but by making other parameters (e.g. recharge, transmissivity, storativity etc.) less reasonable. Since there is less known about these other parameters, the "loose" constraints on duty and acreage were, in a sense, an independent check on the calibration of the model, assuming that the results were reasonable in comparison to the initial estimates developed by Groeneveld and Baugh (2002).

The analysis in this section provides an overview of an analysis of the pumping estimates and provides some additional insight into irrigated acreage. The consumptive or net pumping estimates of the three models are summarized in Figure 86. Note that except for a period in the late 1950s, the estimates of all three models are similar and the differences in the late 1950s are not large. Due to the similarities, this analysis uses the estimates from the hybrid model.

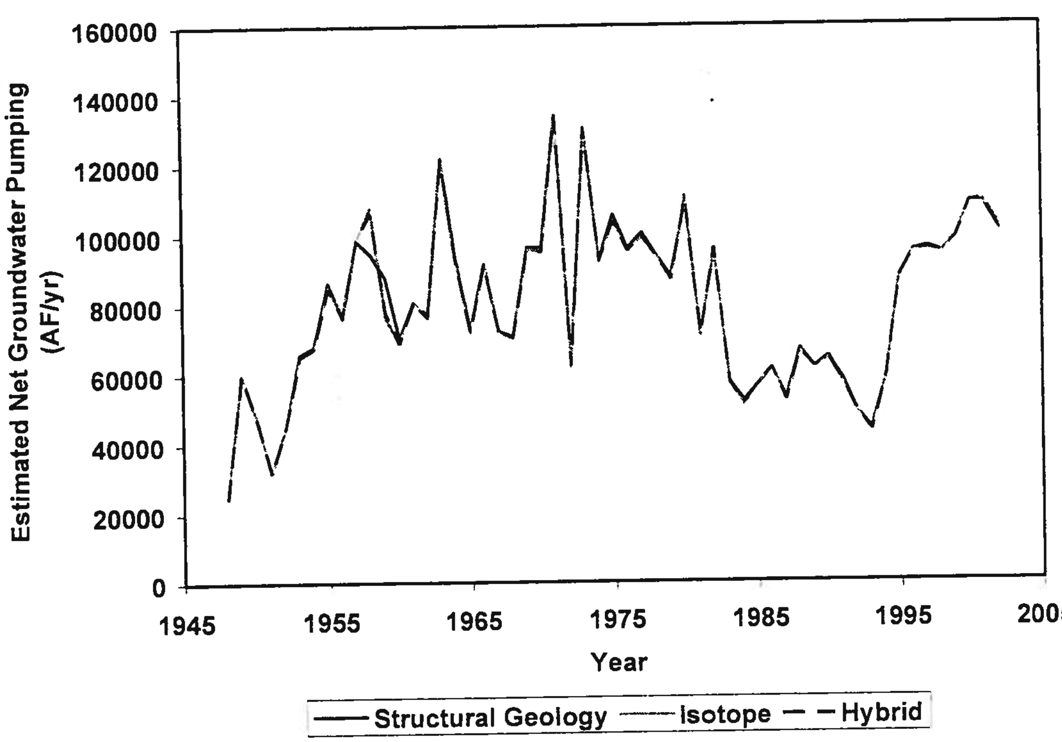


Figure 86. Comparison of Consumptive Groundwater Pumping Estimates from All Three Models

Irrigated acreage can be estimated by dividing the estimated pumping by an assumed duty. These estimates can then be compared to previous estimates (Ashworth, 1995; Blair, 2002a; Groeneveld and Baugh, 2002). Appendix B-1 presents the estimates of irrigated acreage for each zone for the structural geology model for the period 1974 to 2002; Appendix B-2 presents the estimates of irrigated acreage for each zone for the isotope geochemistry model for the period 1974 to 2002; and Appendix B-3 presents the estimates of irrigated acreage for each zone for the hybrid model for the period 1974 to 2002. This period represents the coverage of the estimates by Groeneveld and Baugh (2002), and the irrigated acreage estimates generated from the model estimated pumping can be compared to the Groeneveld and Baugh (2002) estimates. The discussion in this section presents an overall summary of the irrigated acreage for the entire model domain.

Figure 87 presents the comparison of the irrigated acreage with an assumed duty of 3 AF/acre and previous estimates. Note that there is reasonable agreement in 1960, 1964, 1974, 1984, and 1989. Significant differences are observed in 1958, 1969, 1979, 2000 and 2001.

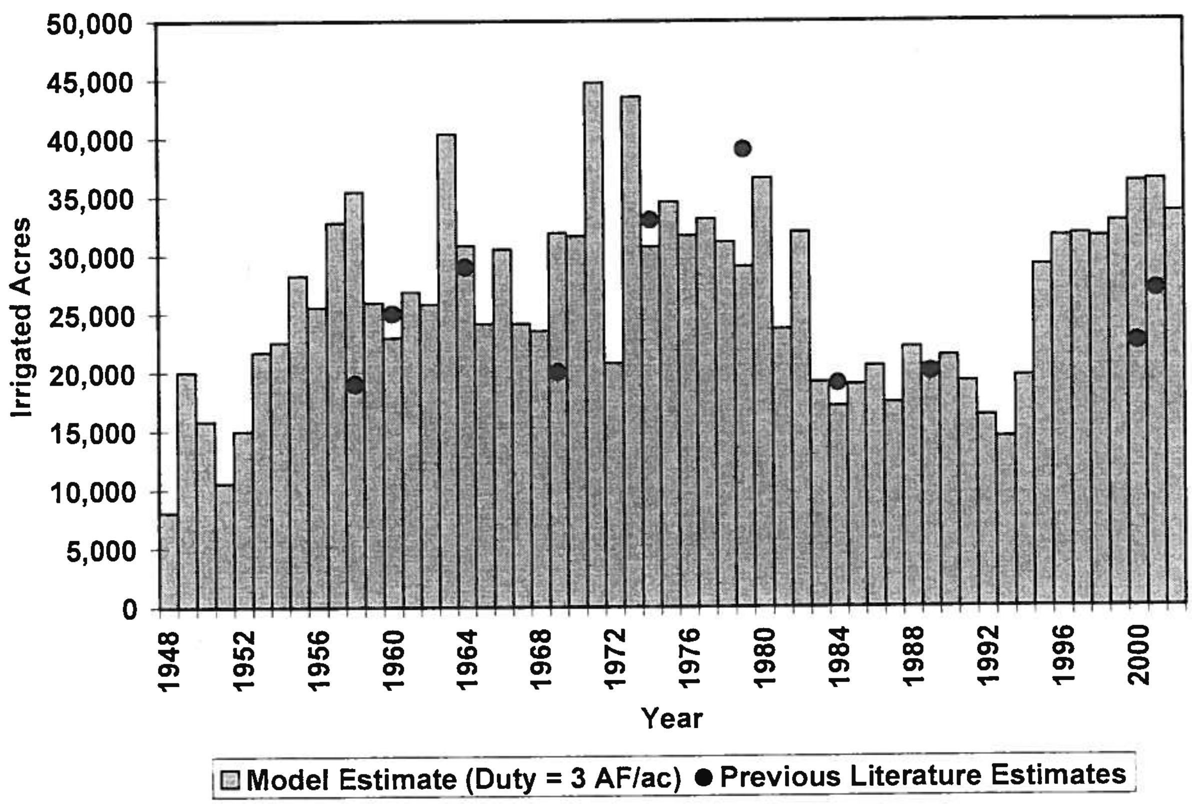


Figure 87. Comparison of Estimated Irrigated Acreage and Previous Literature Estimates Using a Duty of 3 AF/acre

Figure 88 presents the comparison of the irrigated acreage with an assumed duty of 5 AF/acre and previous estimates. Note that there is reasonable agreement in 1958, 1969, and 2000. Significant differences are observed in all other years.

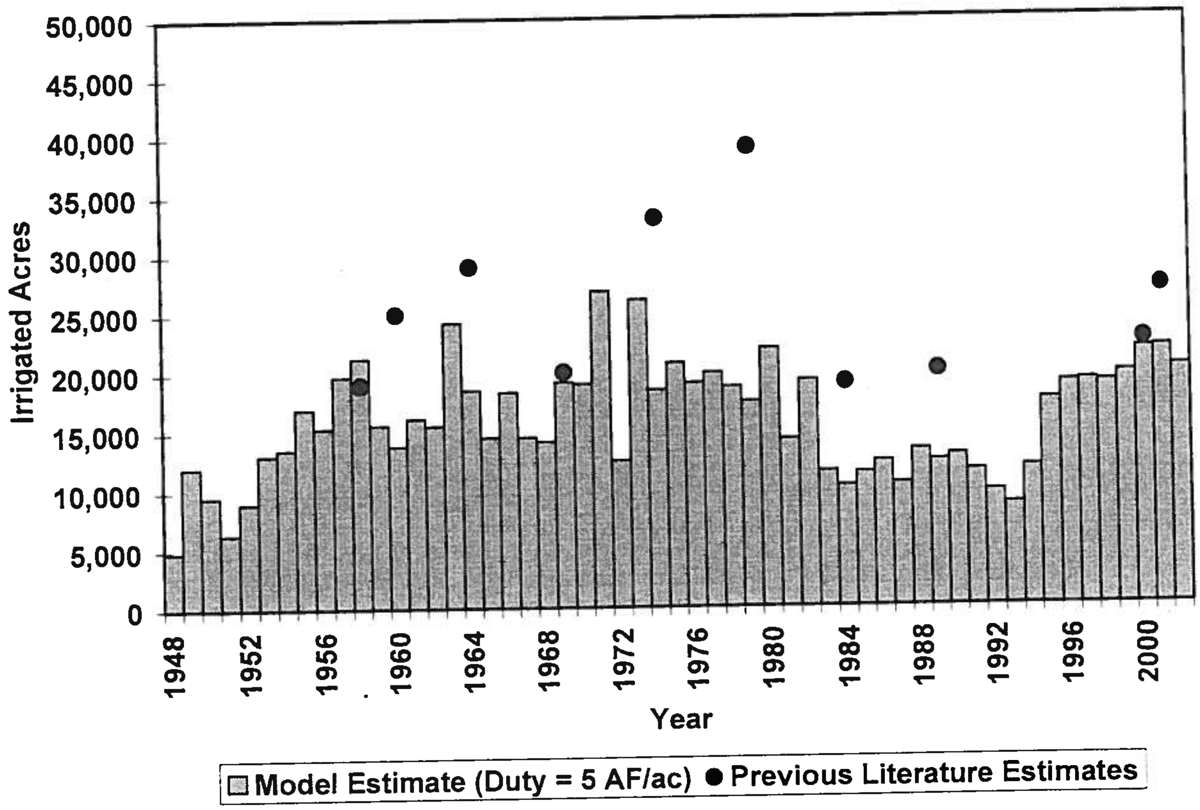


Figure 88. Comparison of Estimated Irrigated Acreage and Previous Literature Estimates Using a Duty of 5 AF/acre

As discussed previously, these literature estimates were based on crop reports, which are reports of irrigated acreage associated with various government farm programs. Irrigated acreage reported in a government crop report did not necessarily receive irrigation water for that particular year. Acreage that is temporarily fallowed is considered "irrigated acreage" in various farm programs. Therefore, it is reasonable to expect that the estimates developed from crop reports and this modeling effort may not agree closely in all cases.

The estimates of Groeneveld and Baugh (2002) were used as initial estimates for developing consumptive or net groundwater pumping estimates for model calibration. Although these initial pumping estimates were adjusted during calibration, it is expected that estimates of irrigated acreage derived from the calibrated pumping estimates would agree reasonably with the irrigated acreage estimates of Groeneveld and Baugh (2002). Figure 89 presents the comparison of the irrigated acreage with an assumed duty of 3 AF/acre and the estimates of Groeneveld and Baugh (2002).

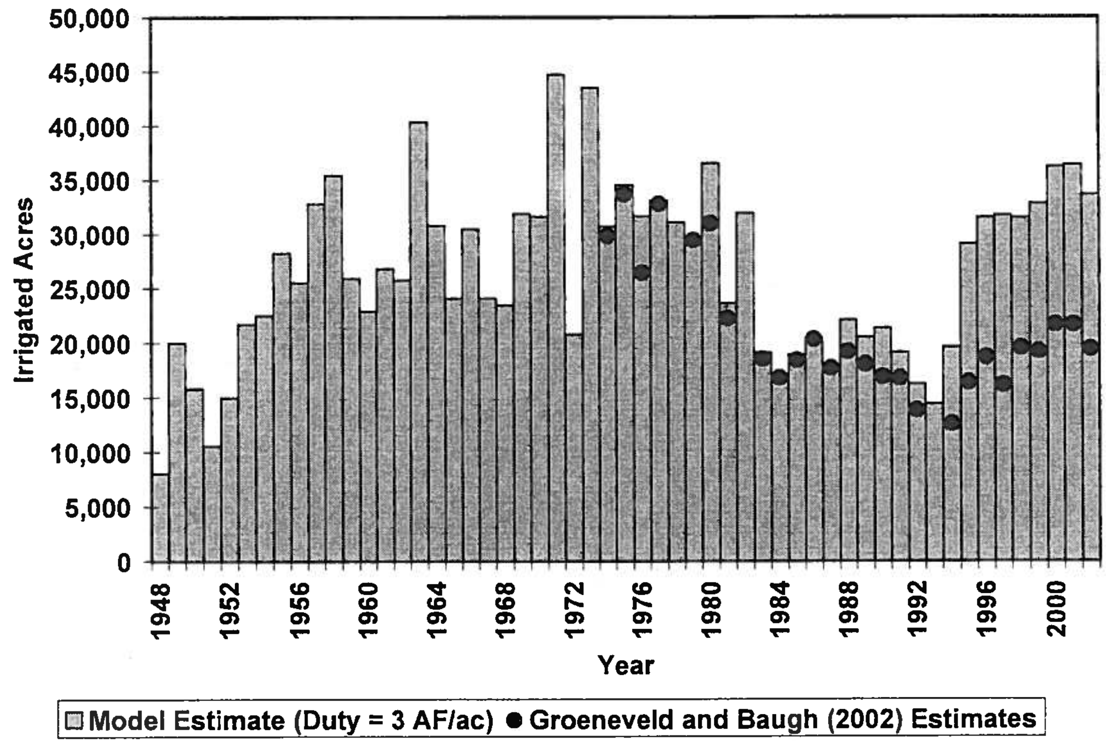


Figure 89. Comparison of Estimated Irrigated Acreage and Groeneveld and Baugh (2002) Estimates Using a Duty of 3 AF/acre

Note the generally good agreement from 1974 to 1992, and the generally poor agreement from 1994 to 2002. This observation is reversed when irrigated acreage estimates are based on an assumed duty of 5 AF/acre as shown in Figure 90. When the duty is assumed to be 5 AF/acre, agreement is poor from 1974 to 1992, and good from 1994 to 2002.

It can also be seen that irrigated acreage generally increased in the late 1940s and early 1950s. Irrigated acreage fluctuated significantly from the late 1950s to the early 1980s. Flood irrigation was common during this time. A general decline in irrigated acreage was observed from the early 1980s to the mid 1990s. Irrigated acreage rose again and has remained relatively constant from the mid 1990s to 2002. Center pivot irrigation has been commonly practiced since the mid 1990s.

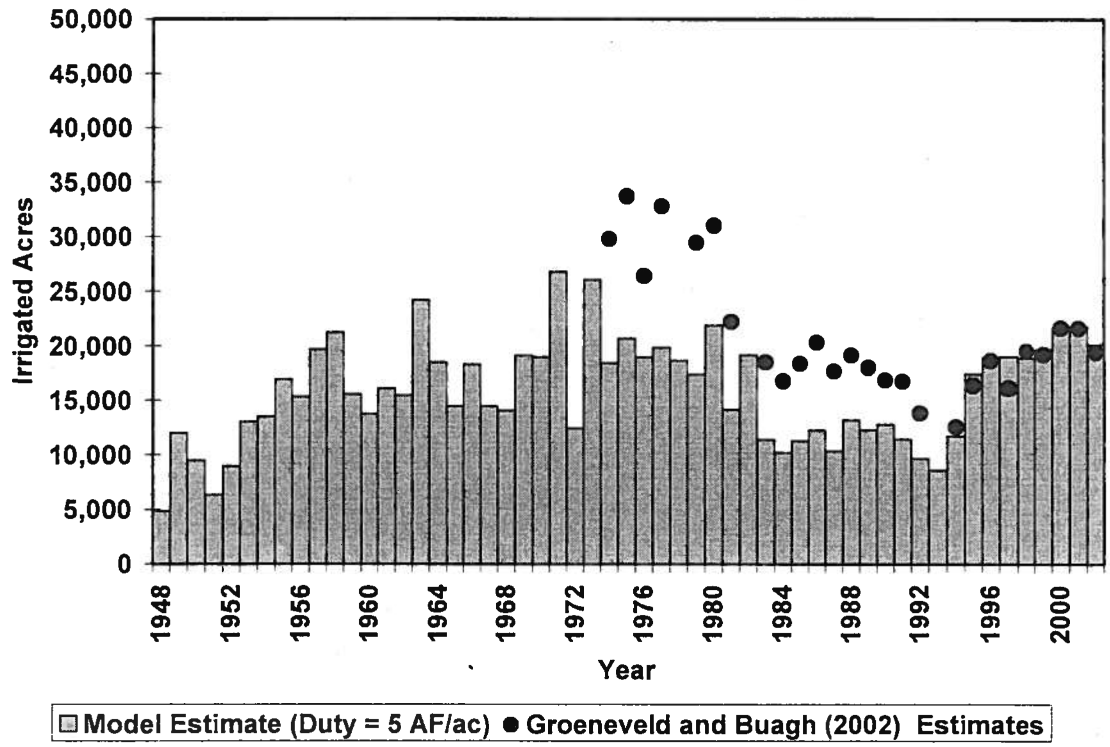


Figure 90. Comparison of Estimated Irrigated Acreage and
Groeneveld and Baugh (2002) Estimates Using a Duty of 5 AF/acre

Based on this analysis, it appears that consumptive pumping prior to 1993 was on the order 3 AF/ac. Flood irrigation typically results in high total pumping and significant infiltration of return water. Because the model relies on estimates of consumptive or net pumping and includes an underlying assumption that irrigation water infiltrates back to the water table within the year in which it was pumped, this modeling analysis can provide no insight into estimates of total pumping, or, by extension, the amount of water that infiltrates back to the aquifer (i.e. the leaching fraction).

After 1993 (i.e. after the dominance of center pivot irrigation), it appears that the consumptive or net pumping is about 5 AF/ac. It is possible that total pumping on a per irrigated acre basis has decreased since the period of flood irrigation, but this modeling analysis cannot be used to evaluate this commonly held assumption. It is clear, however, that there is a distinct difference in the consumptive duties before and after the introduction of center pivots as the dominant irrigation method in the area.

Based on this conclusion, Figure 91 presents an interpreted estimate of irrigated acreage in the area. Irrigated acreage rose from less than 10,000 acres in 1948 to about 25,000 acres in the mid 1950s. From the mid 1950s to the mid 1980s, irrigated acreage fluctuated between about 20,000 acres to as high as about 45,000 acres. From the early 1980s to 2002, irrigated acreage has been relatively constant at slightly over 20,000 acres, except for declines in 1993 and 1994.

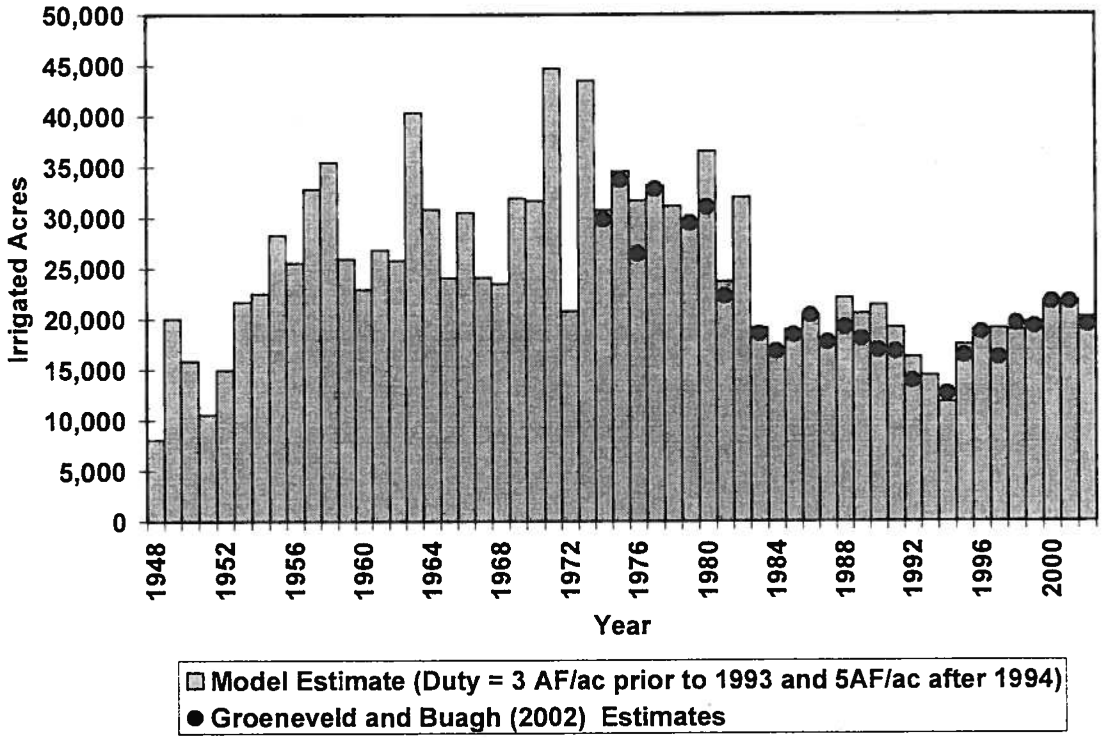


Figure 91. Summary Estimate of Irrigated Acreage

7.3 Water Budget Analysis

Ground water budgets or ground water inventories are developed by quantifying all inflows to a system, all outflows from a system, and the storage change of the system over a specified period of time. Literature on the development of ground water budgets dates back to at least the 1930s with the work of Meinzer (1932). Tolman (1937) noted that, at the time, methods to develop ground water budgets had not reached the accuracy necessary to be accepted by all investigators. This was largely due to extensive data collection requirements and the lengthy time needed to observe the range of hydrologic conditions.

Bredehoeft (2002) reviewed the evolution of analysis of ground water systems. The earliest methods in the 1940s and 1950s revolved around the analysis of flow to a single well. Understanding ground water flow on an aquifer or basin scale became possible with the analog model in the 1950s. Improvements in computer technology in the 1960s and 1970s led to the development of digital computer models or numerical models of ground water flow. By 1980, Bredehoeft (2002) reported that numerical models had replaced analog models in the investigations of aquifer dynamics. The principal objective of such models is to understand the impacts of pumping on the system.

A groundwater system is in near steady-state (or near equilibrium) prior to development (prior to groundwater pumping for irrigation or other human use) is shown in Figure 92. In this condition, groundwater inflow equals groundwater outflow and no change in storage occurs over time.

Inflows can include recharge from precipitation, recharge from streamflow, and inflows from adjacent basins (where applicable). Outflows can include discharge to surface water bodies (springs, streams and lakes), evapotranspiration through shallow groundwater vegetation and evaporation (including playa discharge), and outflow to adjacent basins.

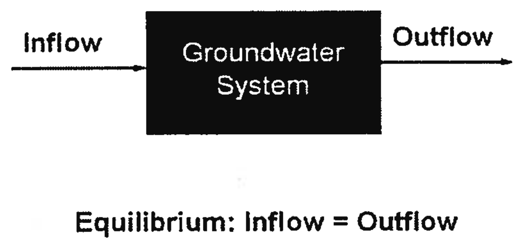


Figure 92. Groundwater System Prior to Development
(after Alley and others, 1999)

Development of groundwater resources (i.e. pumping of wells) results in three "impacts" to the system that is in "near steady-state": 1) storage decline (manifested in the form of lowered groundwater levels), 2) induced inflow (generally manifested by increased surface water recharge or increased groundwater inflow from outside the area of interest), and 3) captured natural outflow (generally manifested in decreased spring flows, decreased stream baseflow, decreased evapotranspiration, or decreased groundwater outflow outside the area of interest).

The initial response to pumping is a lowering of the groundwater level or a "cone of depression" around the well, which results in a decline in storage. The cone of depression deepens and extends radially with time. As the cone of depression expands, it causes groundwater to move toward the well thereby increasing the inflow to the area around the well.

The cone of depression can also cause a decrease of natural groundwater outflow from the area adjacent to the well and acts to "capture" this natural outflow. If the cone of depression causes water levels to decline in an area of shallow groundwater, evapotranspiration (ET) is reduced and the pumping is said to capture the ET. At some point, the induced inflow and captured outflow (collectively the capture of the well) can cause the cone of depression to stabilize or equilibrate.

Figure 93 illustrates the case of a groundwater system after pumping begins. Note that the groundwater storage is decreased, inflow is increased, and outflow is decreased in response to the pumping. The inflow does not equal the total outflow (natural outflow plus pumping). The system is not in equilibrium, and groundwater storage is decreasing.

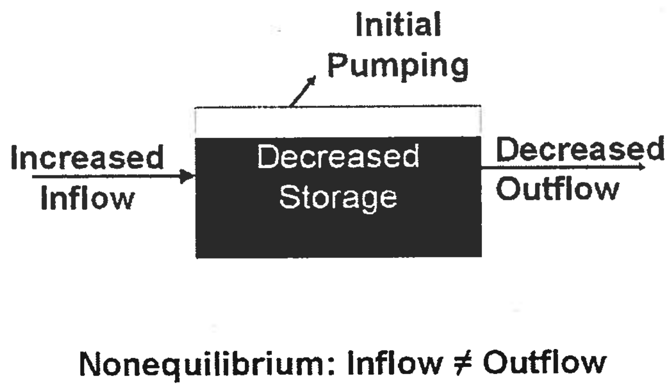


Figure 93. Groundwater System after Initial Pumping
(after Alley and others, 1999)

If the hydraulic conductivity is sufficiently large and initial pumping rate is relatively constant, the inflow and natural outflow will adjust to a new near steady-state condition in response to the pumping. Groundwater storage is decreased from the predevelopment level. This reduction in storage is the result of the new near steady-state condition of the system because the location and the nature of the outflow have changed (i.e. pumping wells). Figure 94 presents a diagram of this new near steady-state or new equilibrium condition.

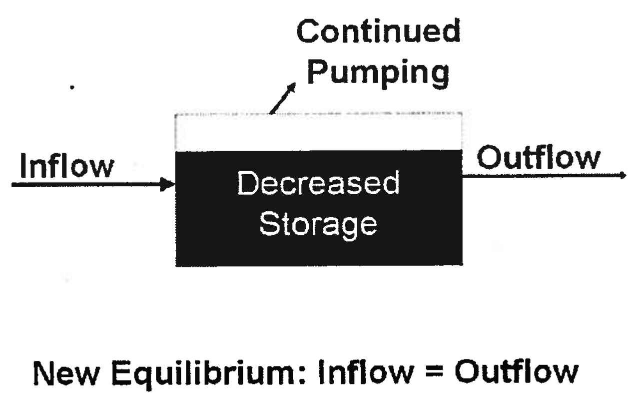


Figure 94. Groundwater System under Continued Pumping – New Equilibrium Condition
(after Alley and others, 1999)

If pumping were to increase after this new near steady-state condition was established, the system inflow increases again, the natural outflow decreases again, and groundwater storage is further decreased. Figure 95 depicts this condition.

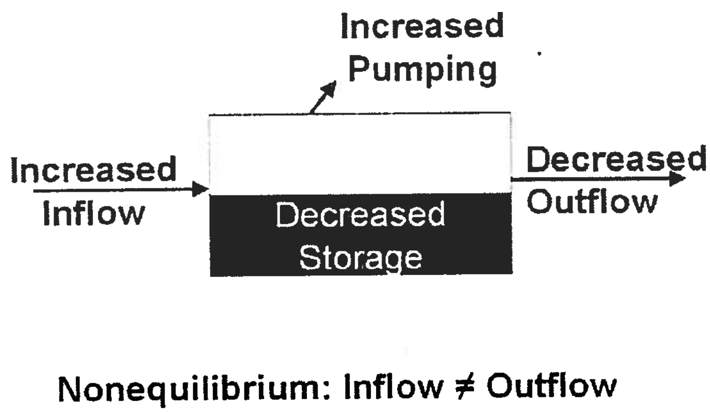


Figure 95. Groundwater System under Additional Increment of Increased Pumping (after Alley and others, 1999)

In response to this new increase in pumping, inflow would continue to increase, outflow would continue to decrease, and storage would continue to decrease as the system is equilibrating. If the pumping is relatively constant, it is possible for a groundwater basin to exhibit stable groundwater levels at a lower level than had been previously observed. Stable groundwater levels are an indication that a new near steady-state condition has been reached.

Pumping can increase to the point where no new near steady-state condition is possible. In this condition, inflow can be induced no further and/or natural outflow can be decreased no further. From an outflow perspective, this condition would be reached once all springs have ceased to flow (no more spring flow to "capture") or the water table has declined to the point that shallow groundwater evapotranspiration has ceased.

In summary, groundwater pumping dynamically alters the direction and magnitude of hydraulic gradients, induces inflow, decreases natural discharge from the system (e.g. evapotranspiration), and affects fluxes between hydraulically connected aquifer systems. Bredehoeft (2002) noted that understanding the dynamic response of a ground water system under pumping stress distills down to understanding the rate and nature of "capture" attributable to pumping, which is the sum of the change in recharge and the change in discharge caused by the pumping. A calibrated numerical ground water model of a region is an ideal tool in meeting the objective of understanding capture. Output from the models includes estimates of various components of the water budget.

Groundwater budgets were developed for the entire model domain of each of the three models. In addition, subregional budgets were developed for each model using ZONEBUDGET (Harbaugh, 1990) to evaluate inflows, outflows and storage changes for four specific regions: 1) original Bone Spring-Victorio Peak aquifer, 2) new Bone Spring-Victorio Peak aquifer, 3) original Hudspeth County Underground Water Conservation District No.1, and 4) new Hudspeth County Underground Water Conservation District No. 1. For all cases, the focus of the analysis was on evaluating the effects of groundwater pumping on "capture" (changes in inflow and changes in natural outflow), and changes in groundwater storage.

7.3.1 Overall Model Domain Groundwater Budgets

The groundwater budgets for the three models for the entire model domain are summarized in Table 31. This summary presents groundwater budgets for the steady state period (pre-1948 or stress period 1) and the average of the transient calibration period (1948 to 2002). Note that all values have been rounded to the nearest 1,000 AF/yr.

Table 31. Summary Groundwater Budgets for the Entire Model Domain
All Values in AF/yr and rounded to nearest 1,000 AF/yr

	Structural Geology		**Isotope Geochemistry**		**Hybrid**	
	Pre-1948 (Steady State)	**1948-2002 Average**	**Pre-1948 (Steady State)**	**1948-2002 Average**	**Pre-1948 (Steady State)**	**1948-2002 Average**
Northern Boundary	41,000	40,000	19,000	19,000	16,000	17,000
Southern Boundary	< 1,000	< 1,000	0	0	0	0
Recharge	63,000	74,000	63,000	70,000	63,000	70,000
Total Inflow	104,000	114,000	82,000	89,000	79,000	87,000
Northwestern Boundary	< 1,000	< 1,000	< 1,000	< 1,000	< 1,000	< 1,000
Southern Boundary	< 1,000	< 1,000	3,000	4,000	< 1,000	2,000
Evapotranspiration	104,000	67,000	79,000	52,000	79,000	49,000
Total Natural Outflow	104,000	67,000	82,000	56,000	79,000	51,000
Groundwater Pumping	0	88,000	0	88,000	0	88,000
Groundwater Storage Decline	0	41,000	0	55,000	0	52,000

The northern boundary inflow for the structural geology model is about twice that of the other two models, and does not change significantly between the steady-state and transient models. The higher flow rate in the structural geology model is apparently due to the high hydraulic conductivity associated with the Otero Break as defined by Mayer (1995), and the higher boundary conductance in the GHB package. Boundary heads in all three models are the same, but the conductance is higher in the structural geology model. This allows more water to flow into the model domain and move towards the Dell City area.

Inflow from the southern boundary (in the area of the groundwater divide) is less than 1,000 AF/yr in the structural geology model in the both the steady state and transient simulations, and is zero in all simulations in the isotope geochemistry and hybrid models.

Recharge in all three models in the steady-state simulation is the same (63,000 AF/yr), but increases in the transient simulations to an average of between 70,000 and 74,000 AF/yr. This is due to the fact that recharge does not increase linearly with precipitation. Recall that the conceptualization of recharge included the assumption that higher precipitation events resulted in a higher infiltration rate. The relationship between precipitation and recharge is presented in Figure 96.

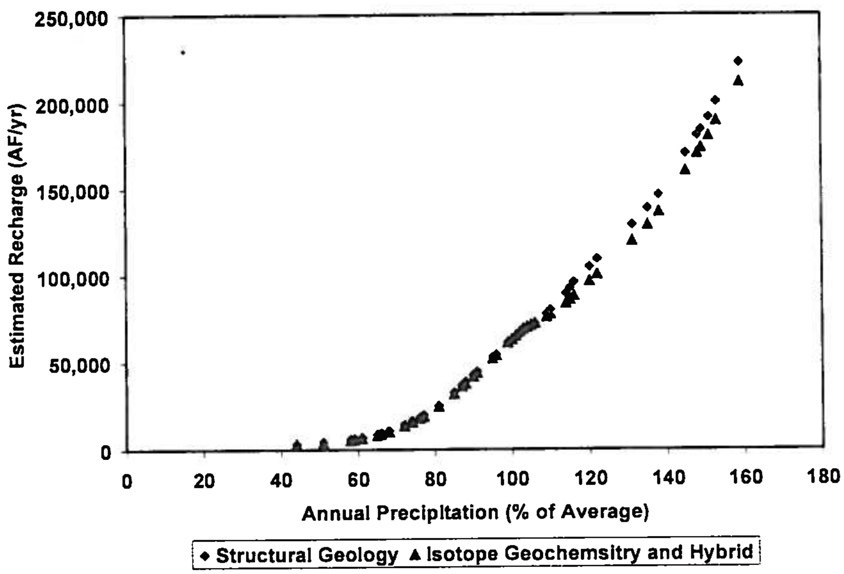


Figure 96. Annual Precipitation vs. Estimated Recharge

Outflow across the northwest boundary is less than 1,000 AF/yr in all models in both the steady-state and transient simulations. Outflow across the southern boundary is less than 1,000 AF/yr in the structural geology model in both the steady-state and transient simulations, and increase slightly in the isotope geochemistry model and hybrid models from the steady state to the transient simulations. This is apparently due to increased recharge as described above. Flow towards San Solomon Spring from this area, therefore, is estimated to range between less than 1,000 AF/yr to 4,000 AF/yr, depending on the model.

Evapotranspiration from the playa is the dominant natural outflow from the system, and decreases from the steady-state to the transient simulations as a result of pumping. Please note also that the total estimated evapotranspiration is higher in the structural geology model than in the other two models due to the higher total inflow of that model resulting from the higher inflow from the northern boundary.

Groundwater pumping in all models averages about 88,000 AF/yr for the transient simulation, and groundwater storage decline ranges from 41,000 AF/yr to 55,000 AF/yr for the three models. Note that the lowest estimated groundwater storage change is from the structural geology model due to the higher inflow/outflow estimates. Groundwater pumping in the structural geology model can "capture" more of outflow since there is more inflow, and as a result, results in less groundwater storage decline than the other models.

Details of the annual changes to the key components of the water budget and discussed more thoroughly in the subsequent sections that deal with the subregional groundwater budgets.

7.3.2 Original Bone Spring-Victorio Peak Aquifer

Although the boundaries of the Bone Spring-Victorio Peak Aquifer have recently changed, an analysis of the groundwater budget of the original aquifer boundaries was completed to compare with previous studies, and to put into perspective the effect of expanding the boundaries of the aquifer. The zones used for this analysis are presented in Figure 97.

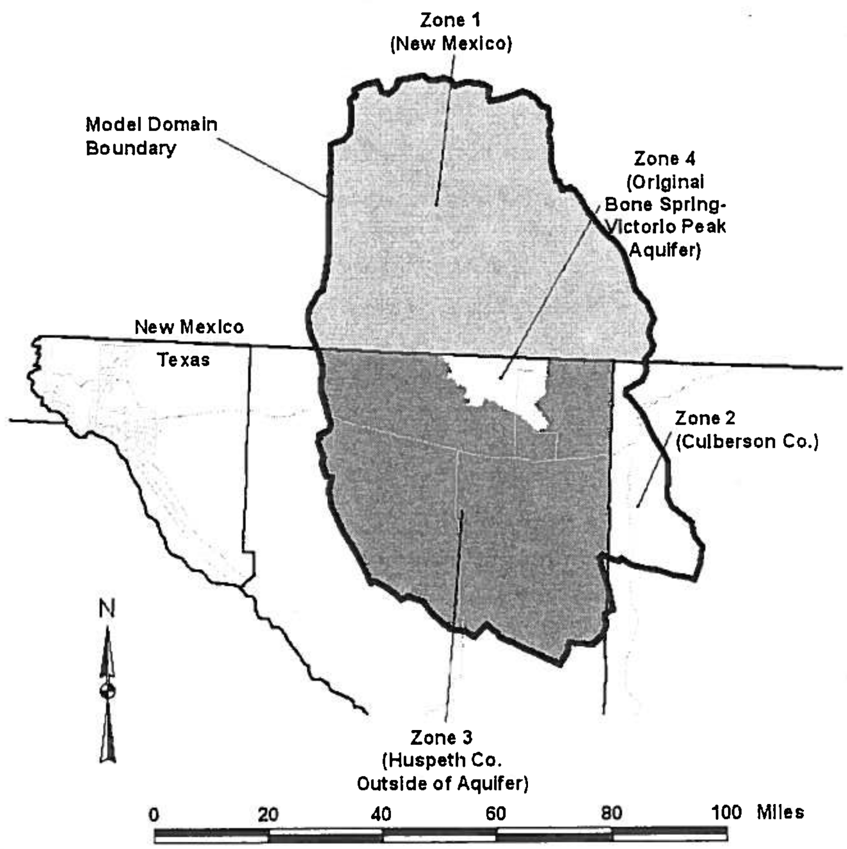


Figure 97. Subregional Zones used for Analysis of Original Bone Spring-Victorio Peak Aquifer

The groundwater budget for Zone 4 (Original Bone Spring-Victorio Peak Aquifer) is summarized in Table 32. Inflow from New Mexico ranges between 43,000 AF/yr and 62,000 AF/yr under the steady-state simulation (pre-1948) depending on the model. The highest value is associated with the structural geology model, and is related to the higher rate of inflow from the northern boundary of the model as described in the overall water budget discussion. Under transient conditions from 1948 to 2002, the inflow from New Mexico increased to between 44,000 and 84,000 as a result of groundwater pumping. Again, the structural geology model represents the highest inflow and the highest increase due to the high northern boundary inflow.

Table 32. Subregional Groundwater Budget for the Original Bone Spring-Victorio Peak Aquifer
All Values in AF/yr

	Structural Geology		Isotope Geochemistry		Hybrid	
	Pre-1948 (Steady State)	1948-2002 Average	Pre-1948 (Steady State)	1948-2002 Average	Pre-1948 (Steady State)	1948-2002 Average
Inflow from New Mexico	62,000	84,000	43,000	56,000	34,000	44,000
Inflow from Hudspeth County Outside Aquifer	0	0	0	8,000	0	18,000
Total Inflow	62,000	84,000	43,000	64,000	34,000	62,000
Outflow to Hudspeth County Outside Aquifer	62,000	14,000	43,000	0	34,000	0
Evapotranspiration	< 1,000	< 1,000	< 1,000	< 1,000	< 1,000	< 1,000
Total Natural Outflow	62,000	14,000	43,000	0	34,000	0
Groundwater Pumping	0	78,000	0	78,000	0	78,000
Groundwater Storage Decline	0	8,000	0	14,000	0	16,000

Under steady-state conditions, flow out of the original boundaries of the Bone Spring Victorio Peak Aquifer Flow ranges between 34,000 AF/yr and 62,000 AF/yr. The high end of the range is associated with the structural geology model, and is a result of the higher inflow. Under transient conditions, the outflow drops in the structural geology model to 14,000 AF/yr. In the other two models the outflow is reduced to zero, and inflow is induced ranging from 8,000 to 18,000. The captured outflow and induced inflow is a result of groundwater pumping.

Evapotranspiration within the original boundaries of the Bone Spring-Victorio Peak aquifer was below 1,000 AF/yr under steady state conditions, and dropped to zero within a few years of the beginning of pumping in 1948. This decrease is due to groundwater pumping, but is insignificant in this analysis due to the limited area of evapotranspiration with the original boundaries of the aquifer. Groundwater pumping is about 78,000 AF/yr, and groundwater storage decline ranged from 8,000 AF/yr to 16,000 AF/yr.

Table 33 summarizes the overall impact of the pumping in terms of increased inflow, decreased (or captured) natural outflow and groundwater storage change. Note that the table summarizes the values in terms of ranges resulting from the results of the three models. Based on this table, the pumping within the original boundaries of the Bone Spring-Victorio Peak aquifer primarily impacted natural outflow into other parts of Hudspeth County, and secondarily induced inflow from New Mexico and caused groundwater storage (i.e. groundwater levels) to decline.

Table 33. Summary of Groundwater Pumping Impacts
Original Bone Spring-Victorio Peak Aquifer

Impact	Flow (AF/yr)
Groundwater Pumping	78,000
Increase in Inflow from New Mexico	10,000 to 22,000
Decreased Outflow to/Induced Inflow from Hudspeth County Outside Aquifer	48,000 to 52,000
Decreased Evapotranspiration within Aquifer	< 1,000
Groundwater Storage Change	8,000 to 16,000

7.3.3 New Bone Spring-Victorio Peak Aquifer

Figure 98 presents the zonation used to analyze the subregional groundwater budget for the new boundaries of the Bone Spring-Victorio Peak Aquifer.

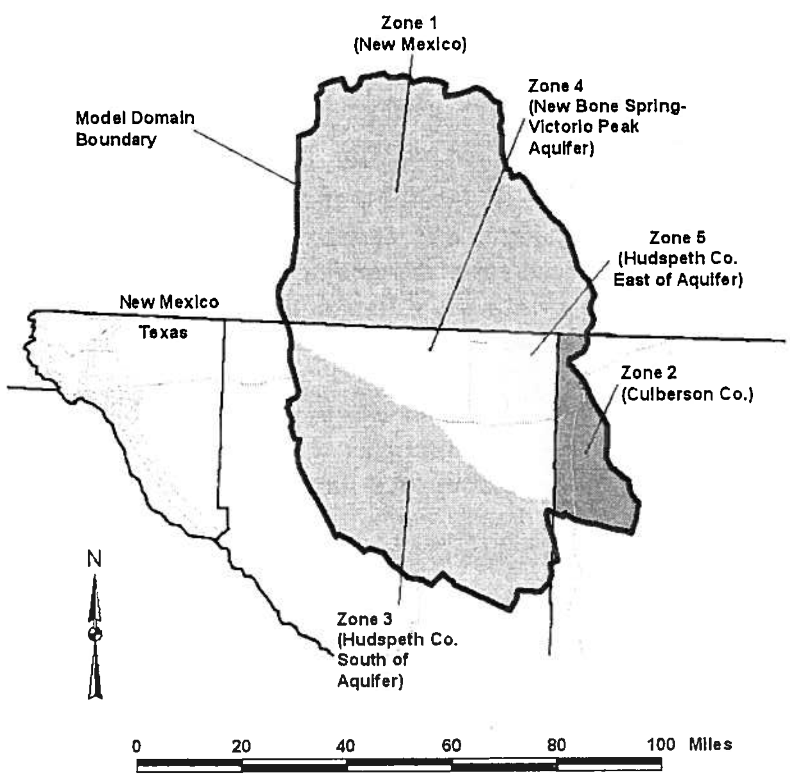


Figure 98. Subregional Zones used for Analysis of New Bone Spring-Victorio Peak Aquifer

The groundwater budget for Zone 4 (New Bone Spring-Victorio Peak Aquifer) is summarized in Table 34. Inflow from New Mexico ranges between 50,000 AF/yr and 69,000 AF/yr under the steady-state simulation (pre-1948) depending on the model. This estimate is higher than the estimate for the original boundaries of the Bone Spring-Victorio Peak Aquifer due to the increase in size and larger flow area along the state line. The highest value is associated with the structural geology model, and is related to the higher rate of inflow from the northern boundary of the model as described in the overall water budget discussion. Under transient conditions from 1948 to 2002, the inflow from New Mexico increased to between 57,000 and 90,000 as a result of groundwater pumping. Again, the structural geology model represents the highest inflow and the highest increase due to the high northern boundary inflow, and these estimates are higher than those from the analysis of the original Bone Spring-Victorio Peak Aquifer boundary.

Table 34. Subregional Groundwater Budget for the New Bone Spring-Victorio Peak Aquifer
All Values in AF/yr

	Structural Geology		**Isotope Geochemistry**		**Hybrid**	
	Pre-1948 (Steady State)	**1948-2002 Average**	**Pre-1948 (Steady State)**	**1948-2002 Average**	**Pre-1948 (Steady State)**	**1948-2002 Average**
Recharge	< 1,000	< 1,000	< 1,000	< 1,000	< 1,000	< 1,000
Inflow from New Mexico	69,000	90,000	53,000	65,000	50,000	57,000
Inflow from Hudspeth County Southwest of Aquifer	4,000	7,000	4,000	14,000	4,000	13,000
Total Inflow	73,000	97,000	57,000	79,000	54,000	70,000
Outflow to Hudspeth County East of Aquifer	26,000	8,000	22,000	11,000	17,000	7,000
Evapotranspiration	47,000	26,000	35,000	19,000	37,000	19,000
Total Natural Outflow	73,000	34,000	57,000	30,000	54,000	26,000
Groundwater Pumping	0	79,000	0	79,000	0	79,000
Groundwater Storage Decline	0	16,000	0	30,000	0	35,000

Under steady-state conditions, inflow from the southwest under steady-state conditions is about 4,000 AF/yr in all models, and increase to between 7,000 AF/yr and 14.000 AF/yr, depending on the model. Note that the largest increases are from the isotope geochemistry and hybrid models which sought to increase flow from the southwest to reflect the findings of Eastoe and Hibbs (2005).

Evapotranspiration within the new boundaries of the Bone Spring-Victorio Peak aquifer ranged between 35,000 AF/yr and 47,000 AF/yr under steady-state conditions and dropped to between

19,000 AF/yr and 26,000 AF/yr under transient conditions. The new Bone Spring-Victorio Peak Aquifer boundary extends far enough to the east to pick over half of the overall evapotranspiration in the model domain. Groundwater pumping is about 79,000 AF/yr, and groundwater storage decline ranged from 16,000 AF/yr to 35,000 AF/yr.

Table 35 summarizes the overall impact of the pumping in terms of increased inflow, decreased (or captured) natural outflow and groundwater storage change. Note that the table summarizes the values in terms of ranges resulting from the results of the three models. Based on this table, the pumping within the new boundaries of the Bone Spring-Victorio Peak aquifer primarily impacted evapotranspiration, flow to Hudspeth County east of the boundary of the Bone Spring-Victorio Peak Aquifer (which is probably additional captured evapotranspiration), and groundwater storage. Secondary effects of the pumping include induced inflows from New Mexico and the area southwest of the Bone Spring-Victorio Peak Aquifer (Diablo Plateau).

Table 35. Summary of Groundwater Pumping Impacts
New Bone Spring-Victorio Peak Aquifer

Impact	Flow (AF/yr)
Groundwater Pumping	79,000
Increase in Inflow from New Mexico	7,000 to 21,000
Increase in Inflow from Hudspeth County Southwest of Aquifer	3,000 to 10,000
Decreased Outflow to Hudspeth County East of Aquifer	18,000 to 36,000
Decreased Evapotranspiration within Aquifer	16,000 to 21,000
Groundwater Storage Change	16,000 to 35,000

7.3.4 Original Hudspeth County Underground Water Conservation District No. 1

Although the boundaries of the Hudspeth County Underground Water Conservation District No. 1 (HCUWCD) have recently changed, an analysis of the groundwater budget of the original HCUWCD boundaries was completed to compare with previous studies, and to put into perspective the effect of expanding the boundaries of the HCUWCD. The zones used for this analysis are presented in Figure 99.

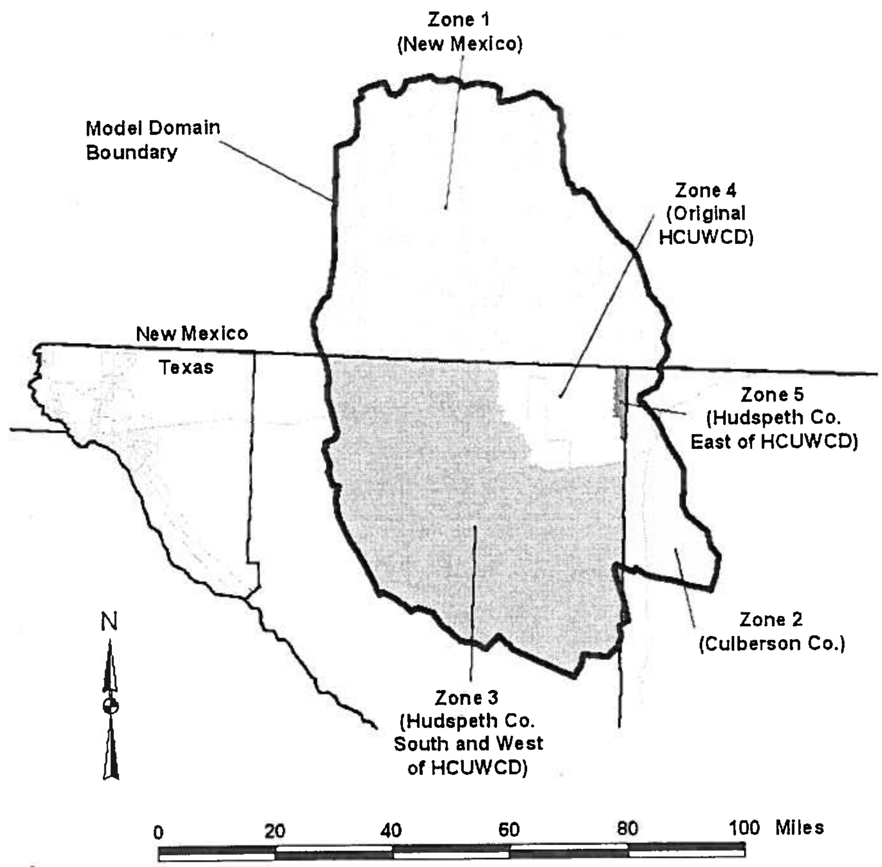


Figure 99. Subregional Zones used for Analysis of the Original Hudspeth County Underground Water Conservation District No.1 (HCUWCD)

The groundwater budget for Zone 4 (Original HCUWCD) is summarized in Table 36. Inflow from New Mexico ranges between 18,000 AF/yr and 51,000 AF/yr. The highest value is associated with the structural geology model, and is related to the higher rate of inflow from the northern boundary of the model as described in the overall water budget discussion. Under transient conditions from 1948 to 2002, the inflow from New Mexico increased to between 25,000 AF/yr and 61,000 AF/yr as a result of groundwater pumping. Again, the structural geology model represents the highest inflow and the highest increase due to the high northern boundary inflow.

Table 36. Subregional Groundwater Budget for the Original Hudspeth County Underground Water Conservation District No.1 (HCUWCD)
All Values in AF/yr

	Structural Geology		**Isotope Geochemistry**		**Hybrid**	
	Pre-1948 (Steady State)	**1948-2002 Average**	**Pre-1948 (Steady State)**	**1948-2002 Average**	**Pre-1948 (Steady State)**	**1948-2002 Average**
Inflow from New Mexico	51,000	61,000	18,000	27,000	22,000	25,000
Inflow from Hudspeth County Southwest of HCUWCD	31,000	50,000	34,000	62,000	37,000	64,000
Inflow from Culberson County	< 1,000	< 1,000	< 1,000	< 1,000	< 1,000	< 1,000
Inflow from Hudspeth County East of HCUWCD	6,000	7,000	7,000	8,000	6,000	7,000
Total Inflow	88,000	118,000	59,000	97,000	65,000	96,000
Evapotranspiration	88,000	52,000	59,000	34,000	65,000	35,000
Total Natural Outflow	88,000	52,000	59,000	34,000	65,000	35,000
Groundwater Pumping	0	80,000	0	80,000	0	80,000
Groundwater Storage Decline	0	14,000	0	17,000	0	19,000

Under steady-state conditions, inflow from the southwest under steady-state conditions ranged between 31,000 AF/yr and 37,000 AF/yr in all models, and increased to between 50,000 AF/yr and 64,000 AF/yr, depending on the model. Note that the largest increases are from the isotope geochemistry and hybrid models which sought to increase flow from the southwest to reflect the findings of Eastoe and Hibbs (2005).

Inflow from Culberson County in the southeastern corner of the original HCUWCD is less than 1,000 AF/yr in both the steady-state and transient simulations, and is considered relatively insignificant. Inflow from Hudspeth County east of the original HCUWCD under steady-state conditions was between 6,000 AF/yr and 7,000 AF/yr, and increased to between 7,000 AF/yr and 8,000 AF/yr under transient conditions.

Evapotranspiration within the original boundaries of the HCUWCD ranged between 59,000 AF/yr and 88,000 AF/yr under steady-state conditions and dropped to between 34,000 AF/yr and 52,000 AF/yr under transient conditions. The original HCUWCD boundary extended far enough to the east to pick over half of the overall evapotranspiration in the model domain. Groundwater pumping is about 80,000 AF/yr, and groundwater storage decline ranged from 14,000 AF/yr to 19,000 AF/yr.

Table 37 summarizes the overall impact of the pumping in terms of increased inflow, decreased (or captured) natural outflow and groundwater storage change. Note that the table summarizes the values in terms of ranges resulting from the results of the three models. Based on this table, the pumping within the original boundaries of the HCUWCD primarily impacted evapotranspiration, flow to Hudspeth County southwest of the original boundaries of HCUWCD, and groundwater storage. Secondary effects of the pumping included induced inflows from New Mexico and the area east of the original boundaries of HCUWCD.

Table 37. Summary of Groundwater Pumping Impacts
Original Hudspeth County Underground Water Conservation District No.1 (HCUWCD)

Impact	**Flow (AF/yr)**
Groundwater Pumping	80,000
Increase in Inflow from New Mexico	3,000 to 10,000
Increase in Inflow from Hudspeth County Southwest of HCUWCD	19,000 to 28,000
Increase in Inflow from Hudspeth County East of HCUWCD	1,000
Decreased Evapotranspiration within HCUWCD	25,000 to 36,000
Groundwater Storage Change	14,000 to 19,000

7.3.5 New Hudspeth County Underground Water Conservation District No. 1

Figure 100 presents the zonation used to analyze the subregional groundwater budget for the new boundaries of Hudspeth County Underground Water Conservation District No.1 (HCUWCD).

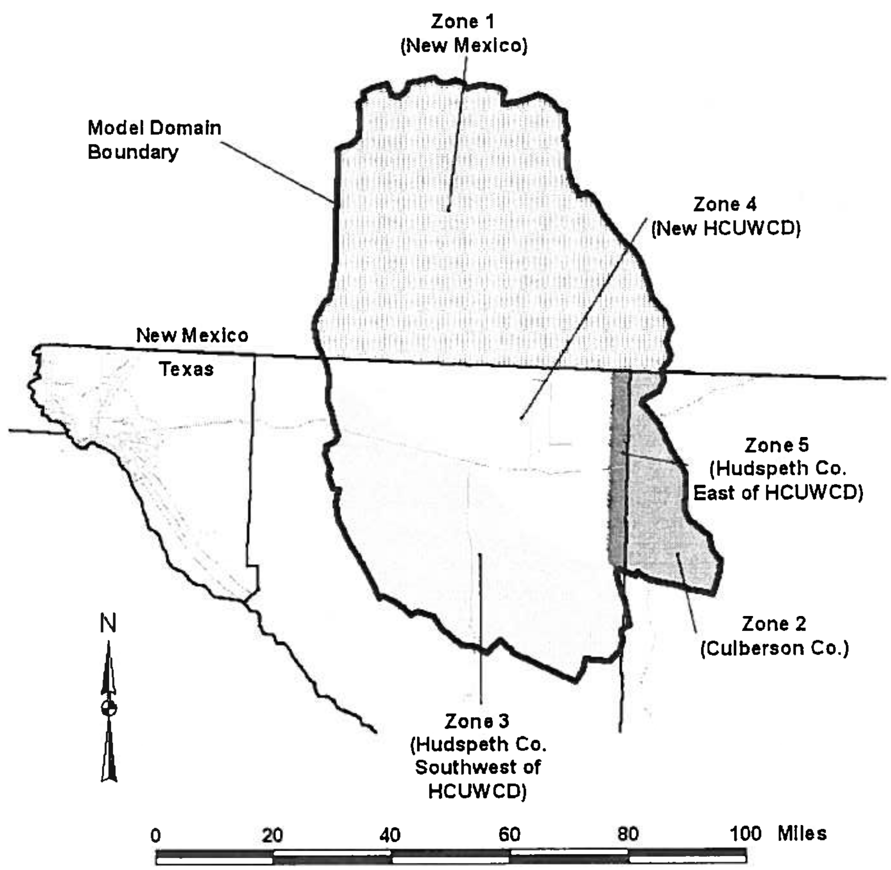


Figure 100. Subregional Zones used for Analysis of the New
Hudspeth County Underground Water Conservation District No.1 (HCUWCD)

The groundwater budget for Zone 4 (New HCUWCD) is summarized in Table 38. Inflow from New Mexico ranges between 53,000 AF/yr and 76,000 AF/yr. This estimate is higher than the estimate for the original boundaries of the HCUWCD due to the increase in size and larger flow area along the state line. The highest value is associated with the structural geology model, and is related to the higher rate of inflow from the northern boundary of the model as described in the overall water budget discussion. Under transient conditions from 1948 to 2002, the inflow from New Mexico increased to between 56,000 AF/yr and 95,000 AF/yr as a result of groundwater pumping. Again, the structural geology model represents the highest inflow and the highest increase due to the high northern boundary inflow, and these estimates are higher than those from the analysis of the original HCUWCD boundary.

Table 38. Subregional Groundwater Budget for the New Hudspeth County Underground Water Conservation District No.1 (HCUWCD)
All Values in AF/yr

	Structural Geology		Isotope Geochemistry		Hybrid	
	Pre-1948 (Steady State)	**1948-2002 Average**	**Pre-1948 (Steady State)**	**1948-2002 Average**	**Pre-1948 (Steady State)**	**1948-2002 Average**
Inflow from New Mexico	76,000	95,000	54,000	65,000	53,000	56,000
Inflow from Hudspeth County Southwest of HCUWCD	3,000	5,000	4,000	13,000	3,000	10,000
Inflow from Hudspeth County East of HCUWCD	9,000	10,000	3,000	4,000	9,000	9,000
Recharge	<1,000	<1,000	<1,000	<1,000	<1,000	<1,000
Total Inflow	88,000	110,000	61,000	82,000	65,000	75,000
Evapotranspiration	88,000	51,000	61,000	36,000	65,000	34,000
Total Natural Outflow	88,000	51,000	61,000	36,000	65,000	34,000
Groundwater Pumping	0	80,000	0	80,000	0	80,000
Groundwater Storage Decline	0	21,000	0	34,000	0	39,000

Under steady-state conditions, inflow from the southwest under steady-state conditions ranged between 3,000 AF/yr and 4,000 AF/yr and increased only slightly to between 5,000 AF/yr to 13,000 AF/yr. These estimates are significantly less than the flow from the southwest for the original boundaries of the HCUWCD, and suggest that the area that contributed flow southwest of the original boundary of HCUWCD is now part of the HCUWCD. Note that the largest increases are from the isotope geochemistry and hybrid models which sought to increase flow from the southwest to reflect the findings of Eastoe and Hibbs (2005).

Inflow from Hudspeth County east of the original HCUWCD under steady-state conditions was between 3,000 AF/yr and 9,000 AF/yr, and increased to between 4,000 AF/yr and 10,000 AF/yr under transient conditions. The new boundary of the HCUWCD extends to the higher elevation areas to the west of Dell City so that some recharge from rainfall is estimated. However, these values are less than 1,000 AF/yr under both the steady-state and transient conditions, and are considered relatively insignificant.

Evapotranspiration within the original boundaries of the HCUWCD ranged between 61,000 AF/yr and 88,000 AF/yr under steady-state conditions and dropped to between 34,000 AF/yr and 51,000 AF/yr under transient conditions. The difference in the eastern boundary of the original HCUWCD and the new HCUWCD appeared to have no significant effect on estimates of evapotranspiration. The HCUWCD still extends far enough to the east to account for over half of the overall evapotranspiration in the model domain. Groundwater pumping is about 80,000 AF/yr, and groundwater storage decline ranged from 21,000 AF/yr to 39,000 AF/yr, which is higher than the estimates for the original boundaries of the HCUWCD. This suggests that, although there is no significant pumping in the "new" portions of the HCUWCD, the cone of depression has extended into this area as evidenced by the larger estimated groundwater storage decline.

Table 39 summarizes the overall impact of the pumping in terms of increased inflow, decreased (or captured) natural outflow and groundwater storage change. Note that the table summarizes the values in terms of ranges resulting from the results of the three models. Based on this table, groundwater pumping within the new boundaries of the HCUWCD primarily impacted evapotranspiration and groundwater storage. Secondary effects of the pumping included induced inflows from New Mexico and the areas southwest and east of the new boundaries of HCUWCD.

Table 39. Summary of Groundwater Pumping Impacts
New Hudspeth County Underground Water Conservation District No.1 (HCUWCD)

Impact	**Flow (AF/yr)**
Groundwater Pumping	80,000
Increase in Inflow from New Mexico	3,000 to 19,000
Increase in Inflow from Hudspeth County Southwest of HCUWCD	2,000 to 9,000
Increase in Inflow from Hudspeth County East of HCUWCD	0 to 1,000
Decreased Evapotranspiration within HCUWCD	25,000 to 37,000
Groundwater Storage Change	21,000 to 39,000

7.3.6 EPWU Capitan Properties

Figure 101 presents the zonation used to analyze the subregional groundwater budget for the EPWU Capitan Reef Properties. The boundaries of Zone 4 are slightly larger than the perimeter boundary of the properties that are owned by EPWU. The objective of this analysis is to develop a quantitative understanding of the flow into and out of the properties in light of historic pumping.

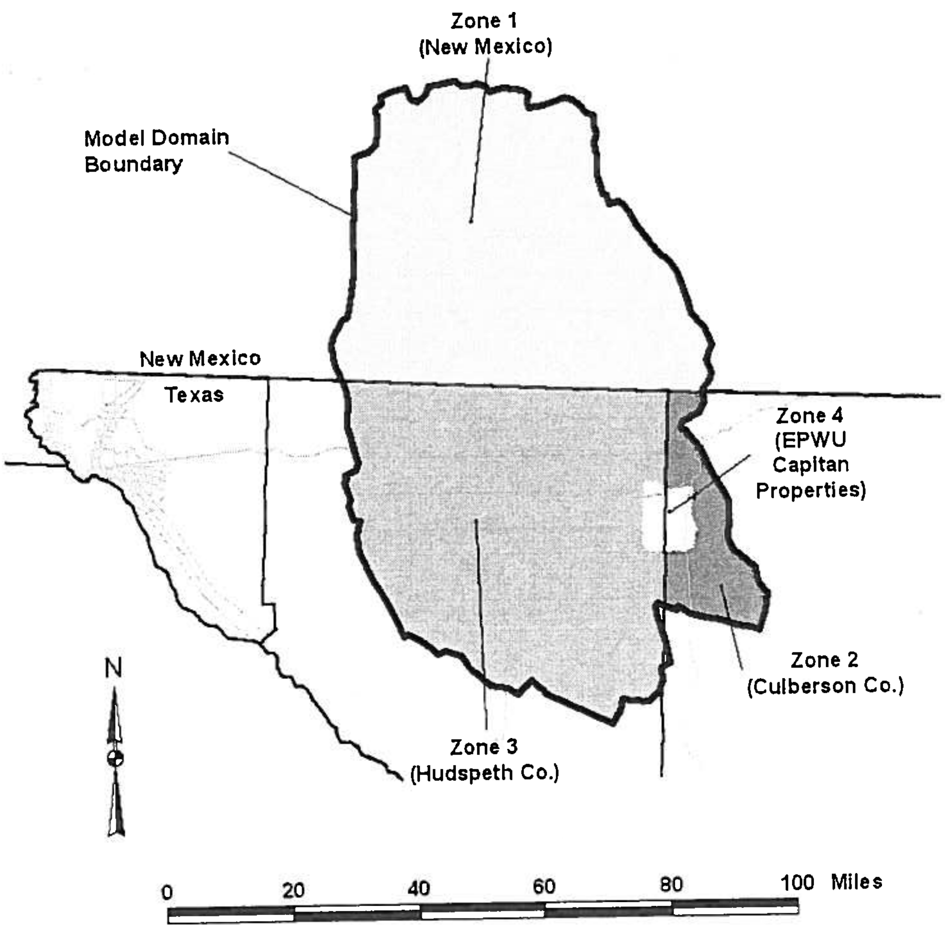


Figure 101. Subregional Zones used for Analysis of the Capitan Reef Properties owned by EPWU

The groundwater budget for Zone 4 (EPWU Capitan Properties) is summarized in Table 40. This table is similar to the ones presented previously for other subregional budgets. However, values are reported to the nearest 100 AF due to the lower flows into and out of the zone.

Inflow from Culberson County ranges between less than 100 AF/yr and 1,700 AF/yr under steady-state conditions, depending on the model. Under transient conditions from 1948 to 2002, the inflow from Culberson County increased to between 800 AF/yr and 2,100 AF/yr as a result of groundwater pumping. Under steady-state conditions, inflow from Hudspeth County was zero in the structural geology and hybrid models, but was 4,000 AF/yr in the isotope geochemistry model.

Inflow from Hudspeth County in the isotope geochemistry model increase to 4,100 AF/yr from 1948 to 2002.

Table 40. Subregional Groundwater Budget for EPWU Capitan Reef Properties
All Values in AF/yr

	Structural Geology		Isotope Geochemistry		Hybrid	
	Pre-1948 (Steady State)	1948-2002 Average	Pre-1948 (Steady State)	1948-2002 Average	Pre-1948 (Steady State)	1948-2002 Average
Inflow from Culberson County	1,700	2,100	< 100	800	1,300	1,600
Inflow from Hudspeth County	0	0	4,000	4,100	0	0
Total Inflow	1,700	2,100	4,000	4,900	1,300	1,600
Outflow to Hudspeth County	600	300	0	0	800	400
Evapotranspiration	1,100	300	4,000	3,200	500	300
Total Natural Outflow	1,700	600	4,000	3,200	1,300	700
Groundwater Pumping	0	2,100	0	2,200	0	2,200
Groundwater Storage Decline	0	600	0	500	0	1,300

Steady-state outflow to Hudspeth County was estimated to be 600 AF/yr in the structural geology model and 800 AF/yr in the hybrid model. This decreased to 300 AF/yr in the structural geology model and to 400 AF/yr in the hybrid model as a result of groundwater pumping. Steady-state evapotranspiration ranged from 500 AF/yr to 4,000 AF/yr, and decreased to between 300 AF/yr and 3,200 AF/yr, depending on the model.

Groundwater pumping was estimated to be between 2,100 AF/yr to 2,200 AF/yr from 1948 to 2002, and the estimated groundwater storage decline during that period was between 500 and 1,300 AF/yr.

Table 41 summarizes the overall impact of the pumping in terms of increased inflow, decreased (or captured) natural outflow and groundwater storage change. Note that the table summarizes the values in terms of ranges resulting from the results of the three models. Based on this table, groundwater pumping within the boundaries of the EPWU Capitan properties primarily impacted groundwater storage. Secondary effects of the pumping included induced inflows from Culberson County and Hudspeth County, and decreased evapotranspiration.

Table 41. Summary of Groundwater Pumping Impacts
EPWU Capitan Reef Properties

Impact	Flow (AF/yr)
Groundwater Pumping	2,100 to 2,200
Increase in Inflow from Culberson County	300 to 800
Increase in Inflow from Hudspeth County	0 to 100
Decreased Outflow to Hudspeth County	0 to 400
Decreased Evapotranspiration	200 to 800
Groundwater Storage Change	500 to 1,300

The analysis of the subregional groundwater budget of the Capitan properties demonstrates that the pumping, although low by comparison to the Dell City area, has caused some modest changes in the inflow and outflow components. However, given the fact that pumping has been variable over the years, it is appropriate to extend the analysis to look at specific periods from 1947 to 2002.

Table 42 presents the subregional groundwater budget for the Capitan Reef properties for the structural geology model. Note that the transient period has been divided into three periods: 1947 to 1970, 1971 to 1994 and 1995 to 2002. This provides the opportunity to examine the impacts of the pumping in more detail, and focus on the increase in pumping since 1995.

Table 42. Subregional Groundwater Budget for Four Time Periods
Capitan Reef Properties Zone
Structural Geology Model
All Values in AF/yr

	Steady-State	1947-1970	1971-1994	1995-2002
Inflow				
Culberson Co.	1,700	2,100	2,100	2,600
Hudspeth Co.	0	0	0	1,700
Total Inflow	1,700	2,100	2,100	4,300
Outflow				
Hudspeth Co.	600	700	500	0
Evapotranspiration	1,100	700	100	0
Groundwater Pumping	0	1,300	2,000	5,200
Total Outflow	1,700	2,700	2,600	5,200
Groundwater Storage Decline	0	600	500	900

Inflow from Culberson County increased from 1,700 AF/yr under steady-state conditions to 2,100 AF/yr in both the 1947 to 1970 and 1971 to 1994 periods. However, when pumping increased from 1995 to 2002, inflow from Culberson County increased to 4,300 AF/yr. Outflow to Hudspeth County ranged between 500 AF/yr and 700 AF/yr during the steady-state and from 1947 to 1994. However, as pumping increased after 1995, the outflow was captured (decreased to zero) and inflow from Hudspeth County was induced at a rate estimated to be 1,700 AF/yr. Evapotranspiration dropped from 1,100 AF/yr under steady-state conditions to zero during the 1995 to 2002 period. Groundwater storage declines were on the order of 500 AF/yr to 600 AF/yr from 1947 to 1994, and increased to about 900 AF/yr from 1995 to 2002. Based on the results of the structural geology model, the primary impact of increased pumping was induced inflow and captured natural outflow, and the secondary impact was groundwater storage decline.

Table 43 presents the subregional groundwater budget for the Capitan Reef properties for the isotope geochemistry model. Like the previous analysis of the structural geology model, the transient period has been divided into three periods: 1947 to 1970, 1971 to 1994 and 1995 to 2002. This provides the opportunity to examine the impacts of the pumping in more detail, and focus on the increase in pumping since 1995.

Table 43. Subregional Groundwater Budget for Four Time Periods
Capitan Reef Properties Zone
Isotope Geochemistry Model
All Values in AF/yr

	Steady-State	1947-1970	1971-1994	1995-2002
Inflow				
Culberson Co.	< 100	700	700	1,800
Hudspeth Co.	4,000	4,100	4,100	4,200
Total Inflow	4,000	4,800	4,800	6,000
Outflow				
Hudspeth Co.	0	0	0	0
Evapotranspiration	4,000	3,800	3,100	2,200
Groundwater Pumping	0	1,400	2,100	5,200
Total Outflow	4,000	5,200	5,200	7,400
Groundwater Storage Change	0	400	400	1,400

Inflow from Culberson County increased from less than 100 AF/yr under steady-state conditions to 700 AF/yr in both the 1947 to 1970 and 1971 to 1994 periods. However, when pumping increased from 1995 to 2002, inflow from Culberson County increased to 1,800 AF/yr. Inflow from Hudspeth County is the dominant inflow component in this model, but does not increase much under pumping conditions, increasing from 4,000 AF/yr in the steady-state period to 4,200 AF/yr from 1995 to 2002. Evapotranspiration dropped from 4,000 AF/yr under steady-state conditions to 2,200 AF/yr during the 1995 to 2002 period. Groundwater storage declines were about 400 AF/yr from 1947 to 1994, and increased to 1,400 AF/yr from 1995 to 2002. Based on the results of the isotope geochemistry model, the primary impact of increased pumping was induced inflow from Culberson County, decreased evapotranspiration, and storage decline, and the secondary impact was induced inflow from Hudspeth County.

Table 44 presents the subregional groundwater budget for the Capitan Reef properties for the hybrid model. Like the previous analyses of the structural geology model and the isotope geochemistry model, the transient period has been divided into three periods: 1947 to 1970, 1971 to 1994 and 1995 to 2002. This provides the opportunity to examine the impacts of the pumping in more detail, and focus on the increase in pumping since 1995.

Table 44. Subregional Groundwater Budget for Four Time Periods
Capitan Reef Properties Zone
Hybrid Model
All Values in AF/yr

	Steady-State	1947-1970	1971-1994	1995-2002
Inflow				
Culberson Co.	1,300	1,700	1,600	1,800
Hudspeth Co.	0	0	0	400
Total Inflow	1,300	1,700	1,600	2,200
Outflow				
Hudspeth Co.	800	800	300	0
Evapotranspiration	500	500	300	100
Groundwater Pumping	0	1,400	2,000	5,200
Total Outflow	1,300	2,700	2,600	5,300
Groundwater Storage Change	0	1,000	1,000	3,100

Inflow from Culberson County increased from 1,300 AF/yr under steady-state conditions to between 1,600 and 1,800 AF/yr from 1947 to 2002. The large increase in pumping from 1995 to 2002 did not induce large amounts of groundwater flow from Culberson County. Outflow to Hudspeth County dropped from 800 AF/yr in the steady-state period to 300 AF/yr from 1971 to 1994, and reversed to induced inflow of 400 AF/yr from 1995 to 2002 as a result of increased pumping. Evapotranspiration dropped from 500 AF/yr under steady-state conditions to 100 AF/yr during the 1995 to 2002 period. Groundwater storage declines were about 1,000 AF/yr from 1947 to 1994, and increased to 3,100 AF/yr from 1995 to 2002. Based on the results of the hybrid model, the primary impact of increased pumping was storage decline, and the secondary impacts were induced inflows from Culberson County, captured outflow and then induced inflow from Hudspeth County and decreased evapotranspiration.

Each model provided different results in terms of origin of inflow, amount of inflows and outflows and degree of change to various inflows and outflows. This highlights the need to present groundwater budgets as ranges and continue to collect data and improve the understanding of the groundwater flow system in the area of the Capitan Reef properties. Data collection efforts are improving since EPWU purchased the properties beginning in 2003.

7.4 Contours of Groundwater Elevation and Drawdown

Contours of groundwater elevation for the steady-state condition and at the end of the transient period (December 2002) for each of the three models are presented in Figures 102 to 107:

- Figure 102 – Steady-state groundwater elevation contours, structural geology model
- Figure 103 – End of simulation groundwater elevation contours, structural geology model
- Figure 104 – Steady-state groundwater elevation contours, isotope geochemistry model
- Figure 105 – End of simulation groundwater elevation contours, isotope geochemistry model
- Figure 106 – Steady-state groundwater elevation contours, hybrid model
- Figure 107 – End of simulation groundwater elevation contours, hybrid model

All three models and both conditions exhibit steep gradients in the area of the Sacramento Mountains and in the area of the Cornudas Mountains. Groundwater flow direction in the structural geology model is strongly controlled by the Otero Break as conceptualized by Mayer (1995), and smaller amounts of flow are derived from the Diablo Plateau. The isotope geochemistry and hybrid models suggest a stronger flow component from the Sacramento Mountains, with contributions from the Diablo Plateau.

Significant differences in the contours are not readily observable between any set of steady-state and end-of-transient simulations due to the 50-ft contour interval. In order to evaluate the effects of pumping more directly, Figures 108 to 110 present drawdown contours due to groundwater pumping for December 2002. Figure 108 presents drawdown contours for the structural geology model, Figure 109 presents drawdown contours for the isotope geochemistry model, and Figure 109 presents drawdown contours for the hybrid model. These contours were estimated by running the models for 50 years with and without pumping. The difference between the calculated groundwater elevations between the two runs was assumed to represent drawdown due to pumping. It can be seen that all three models estimate 20 ft of drawdown about 40 miles into New Mexico along the Otero Break. However, the extent of drawdown west towards the Diablo Plateau is most pronounced in the hybrid model.

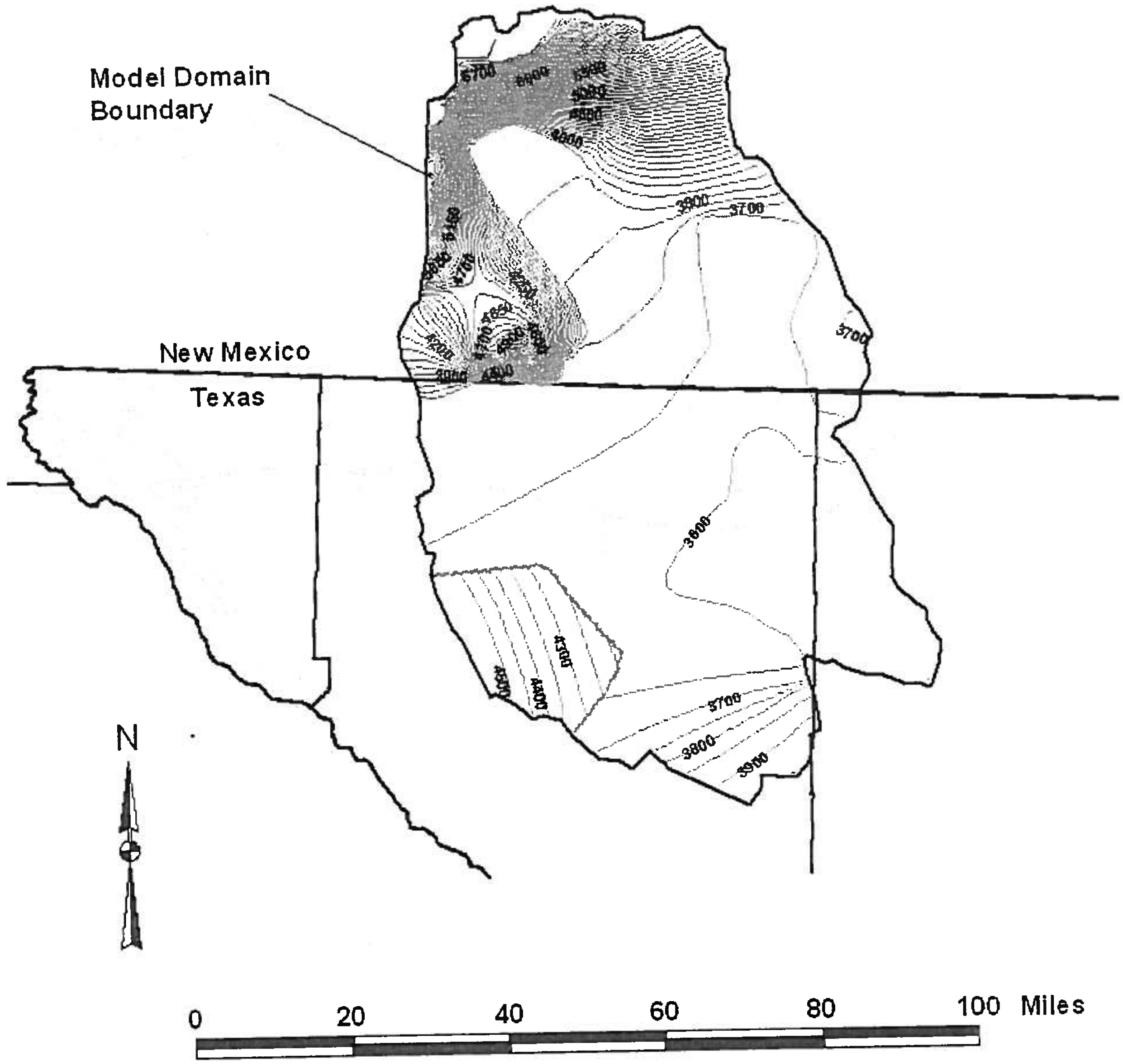


Figure 102. Groundwater Elevation Contours (ft MSL)
Steady State Condition, Structural Geology Model

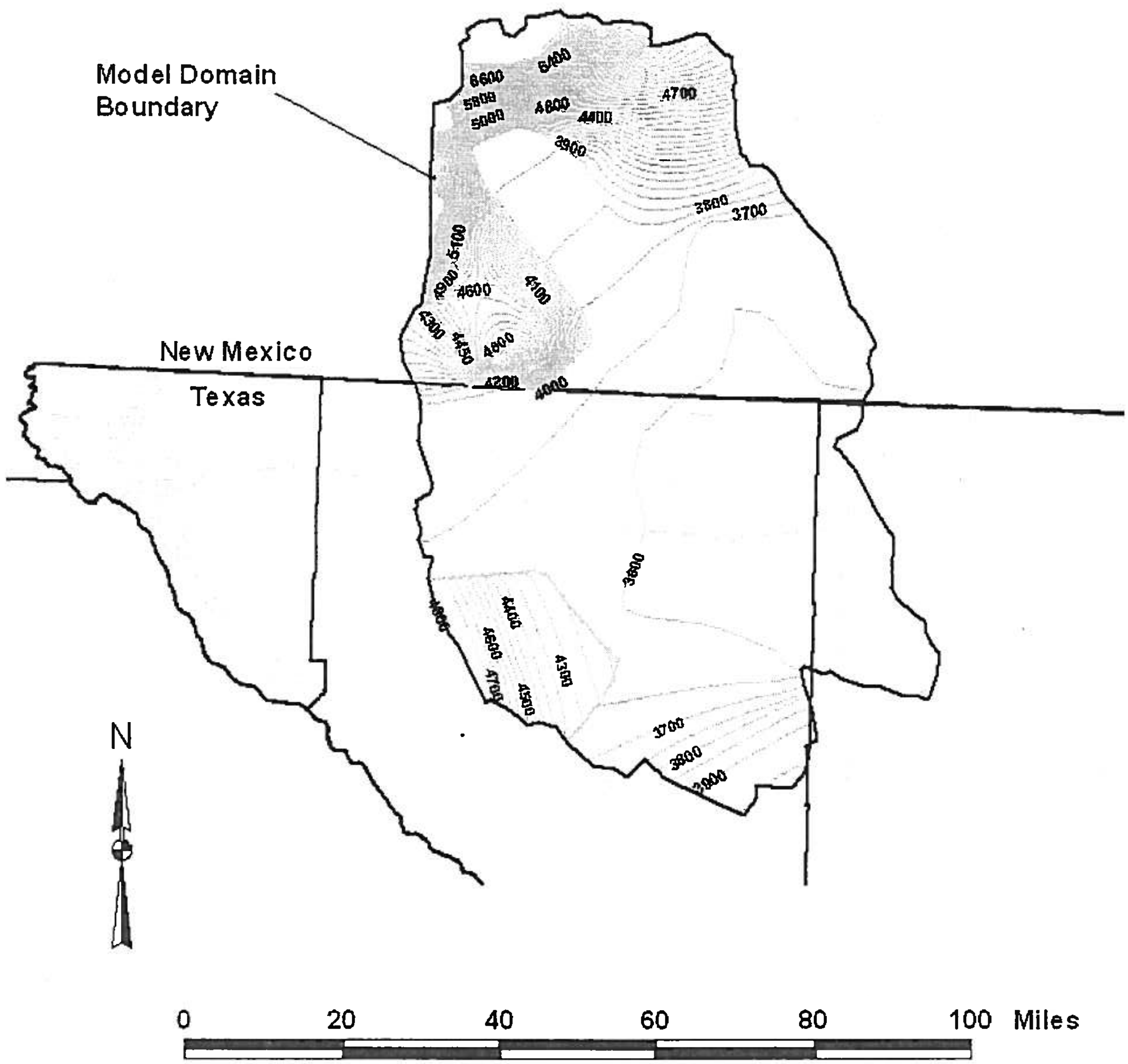


Figure 103. Groundwater Elevation Contours (ft MSL)
End of Transient Simulation (December 2002), Structural Geology Model

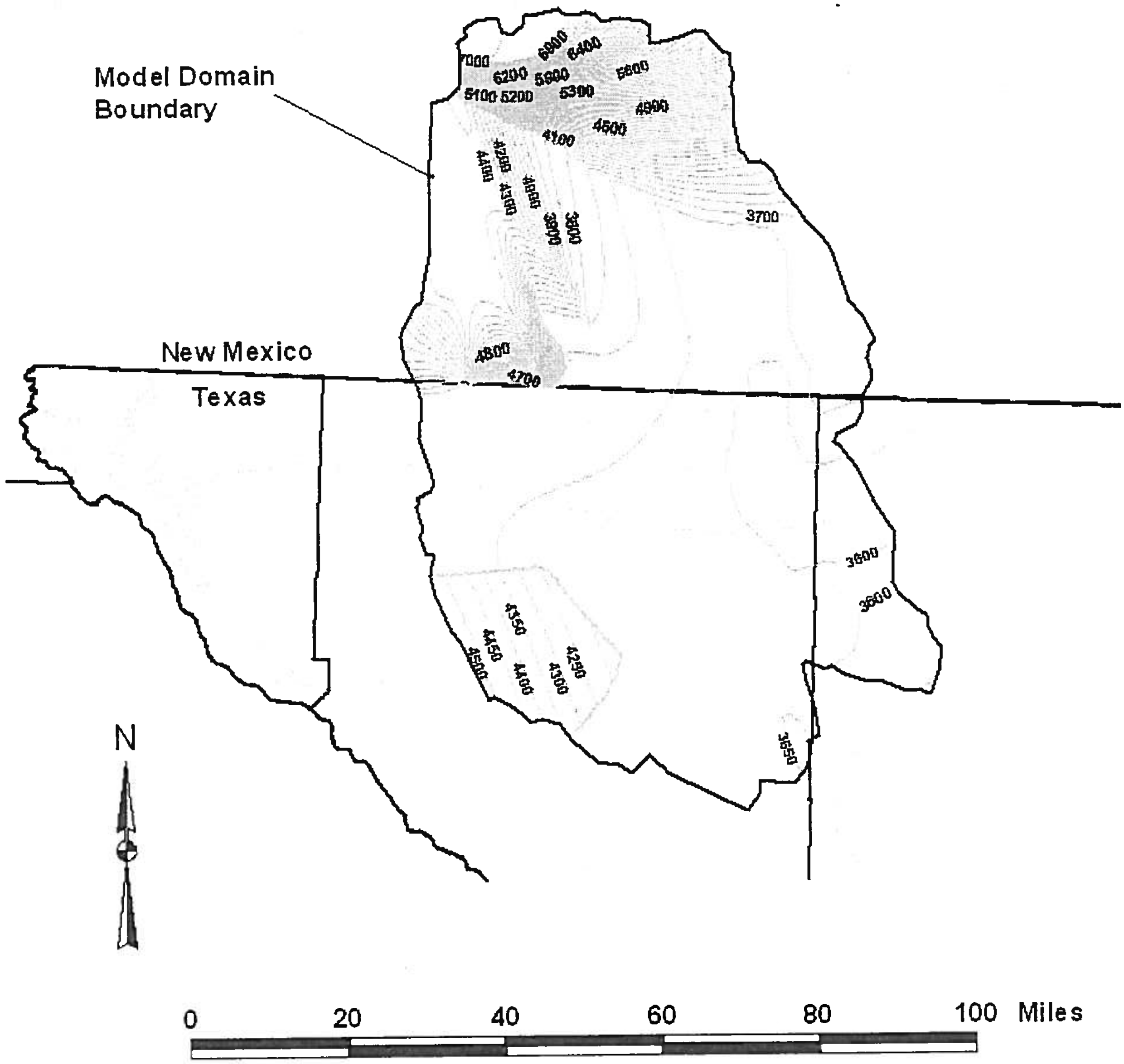


Figure 104. Groundwater Elevation Contours (ft MSL)
Steady-State Conditions, Isotope Geochemistry Model

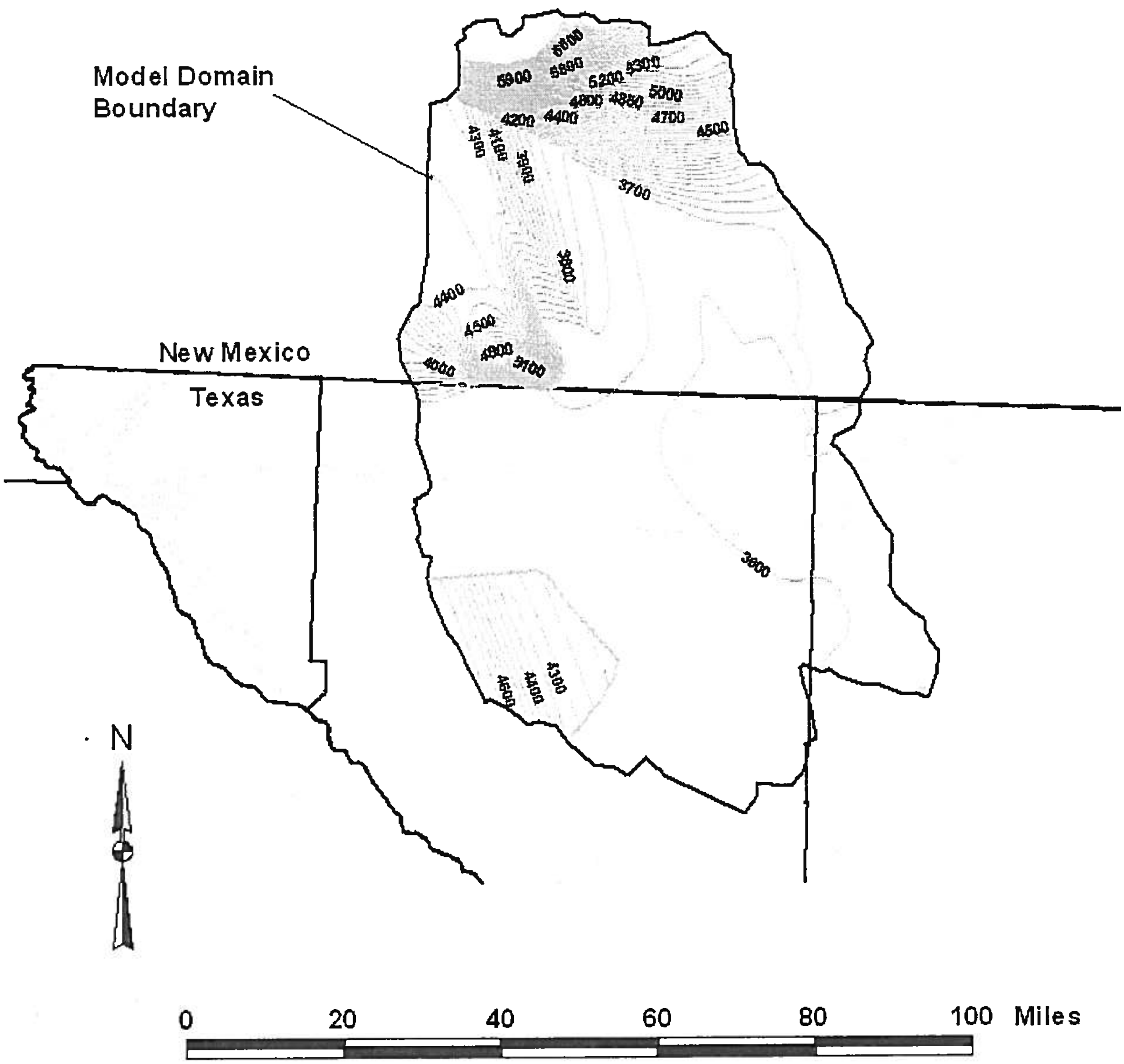


Figure 105. Groundwater Elevation Contours (ft MSL)
End of Transient Simulation (December 2002), Isotope Geochemistry Model

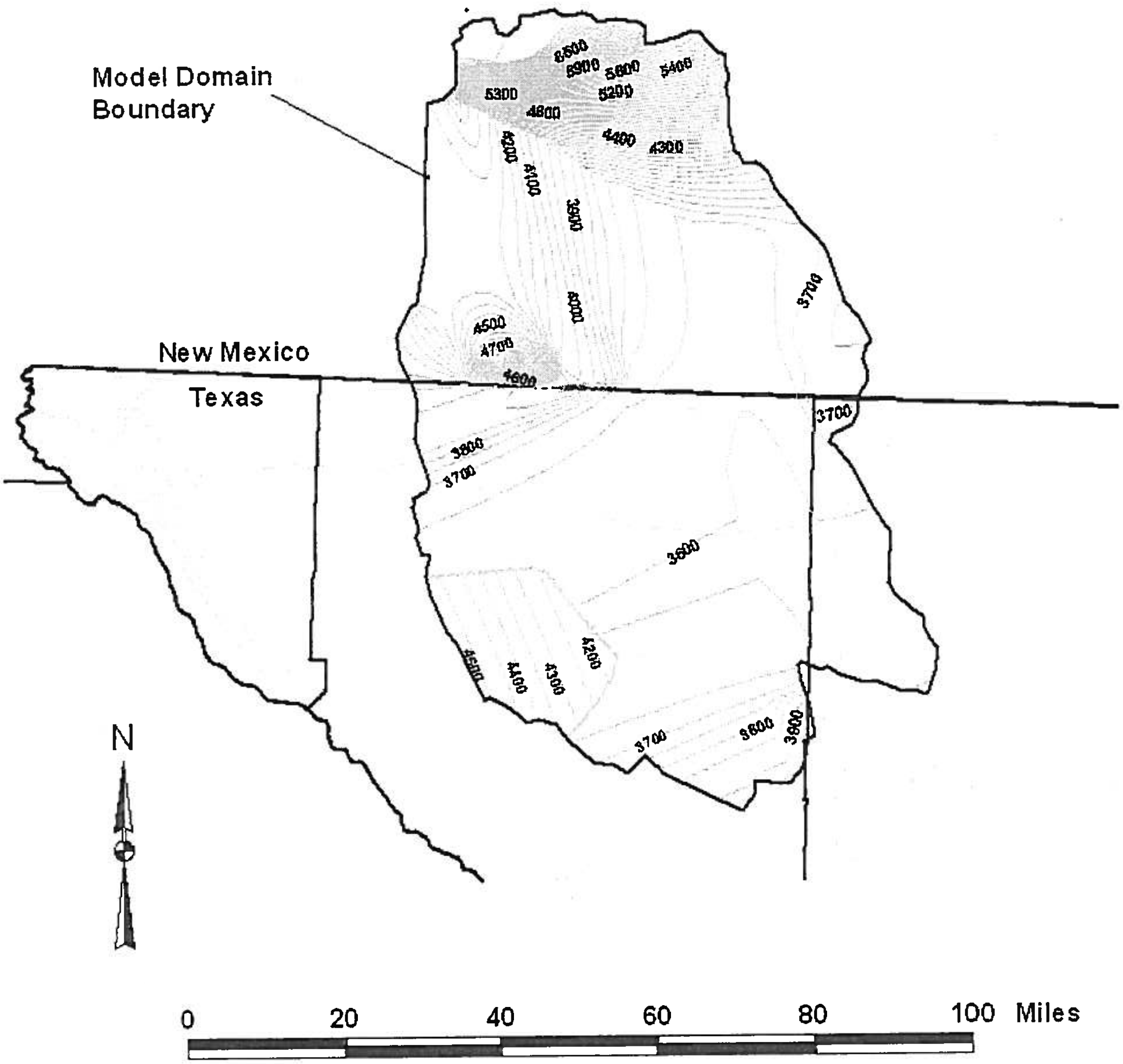


Figure 106. Groundwater Elevation Contours (ft MSL)
Steady-State Conditions, Hybrid Model

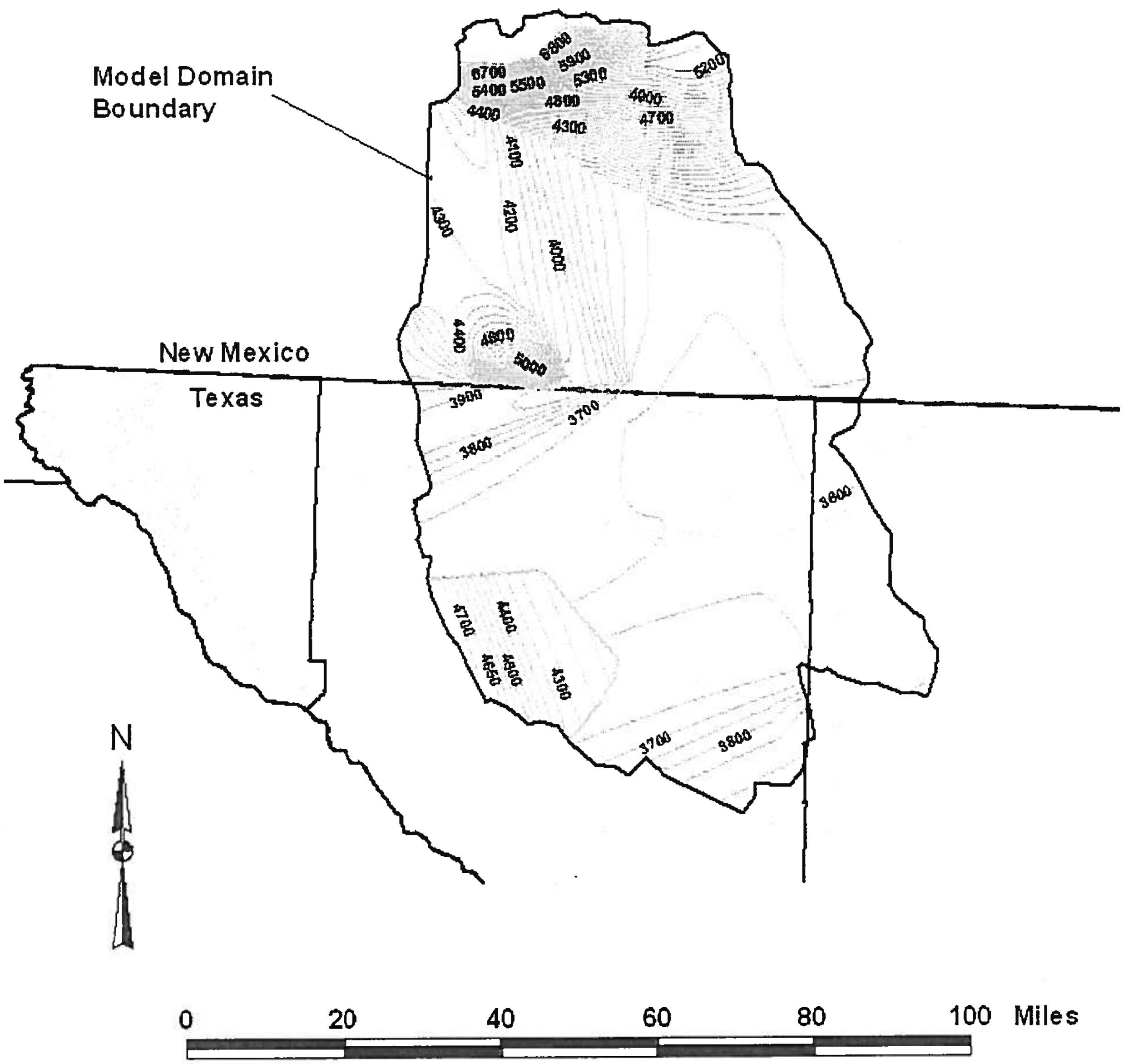


Figure 107. Groundwater Elevation Contours (ft MSL)
End of Transient Simulation (December 2002), Hybrid Model

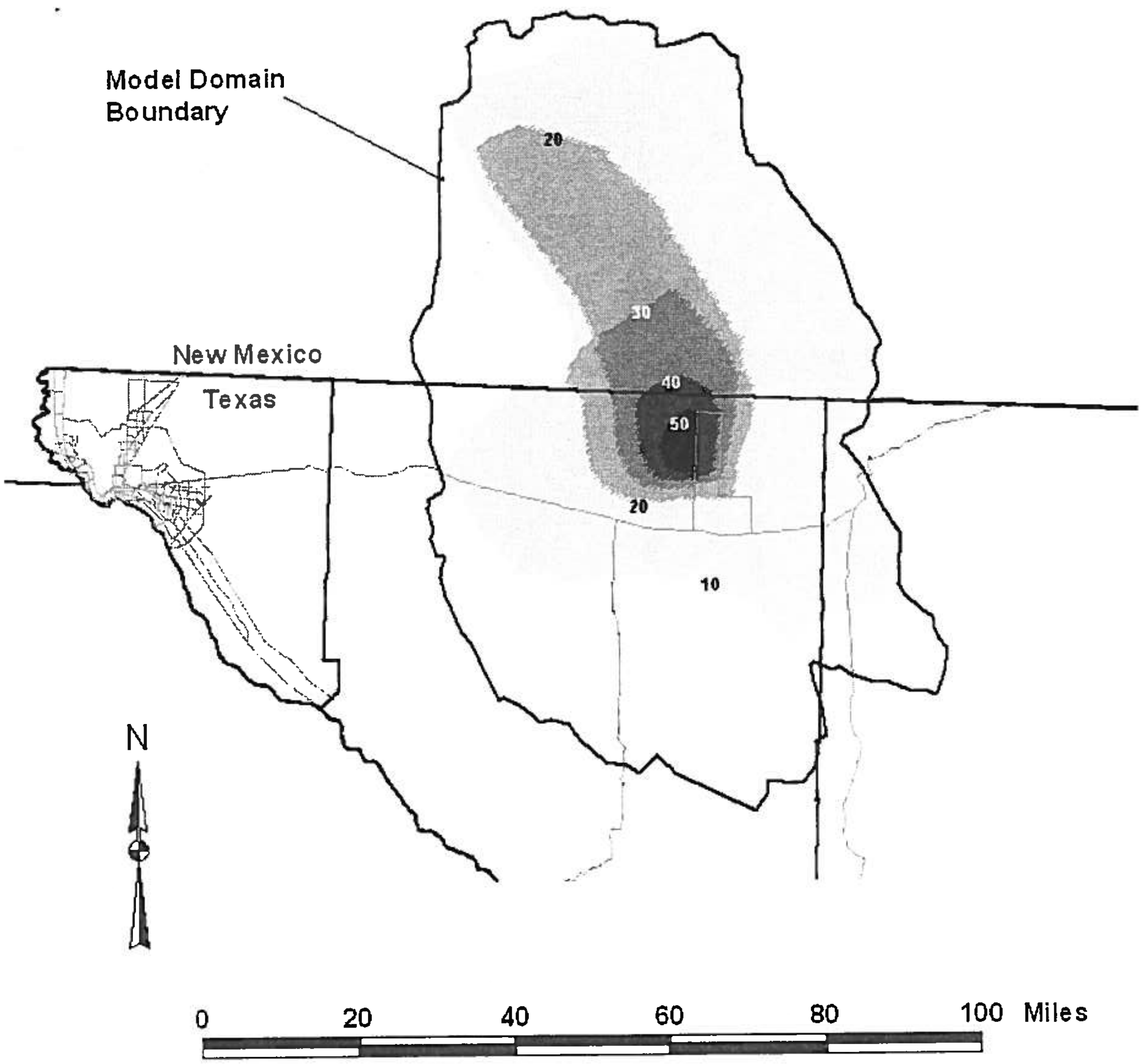


Figure 108. Drawdown (ft) due to Groundwater Pumping from 1948 to 2002
Structural Geology Model

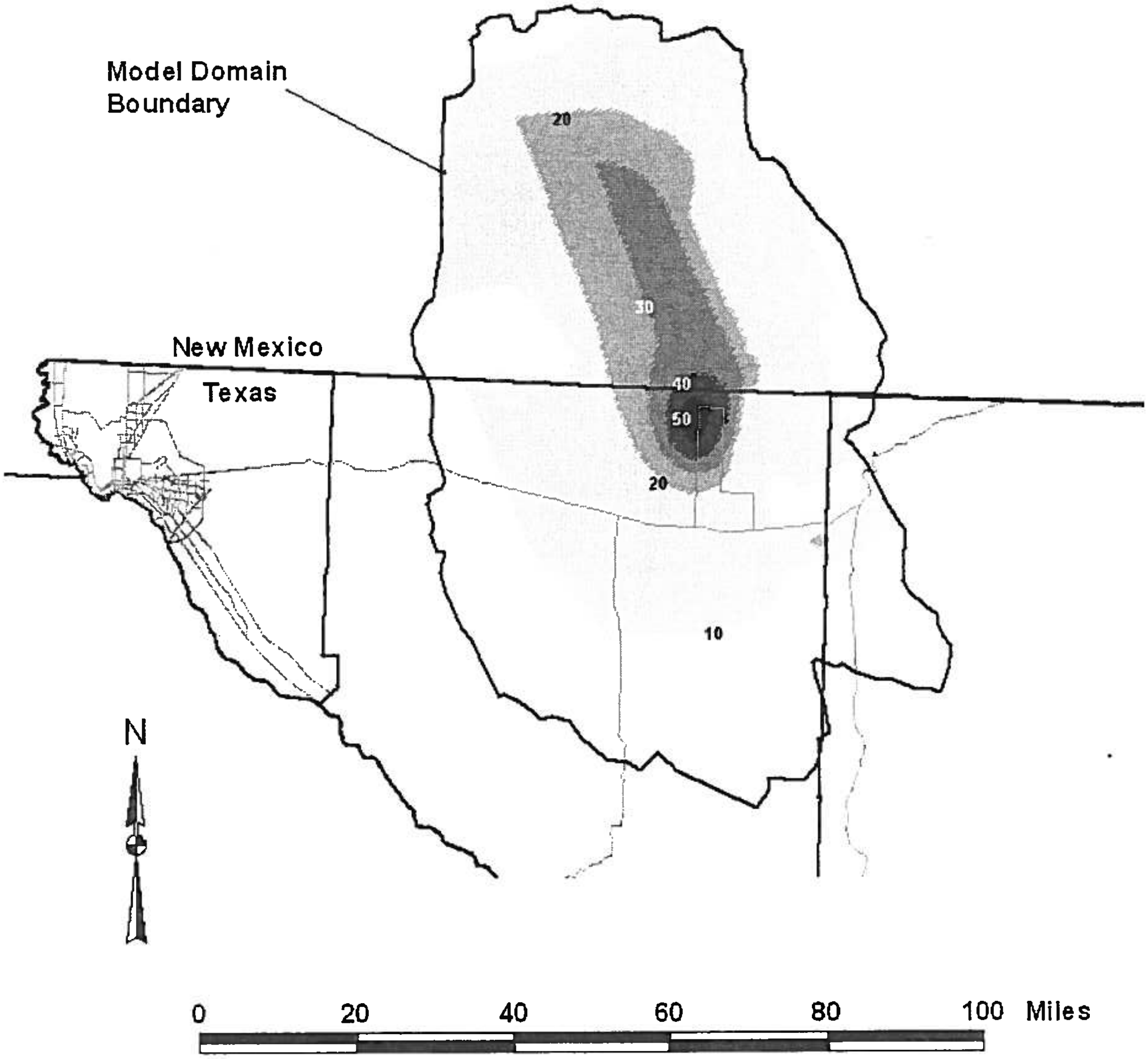


Figure 109. Drawdown (ft) due to Groundwater Pumping from 1948 to 2002
Isotope Geochemistry Model

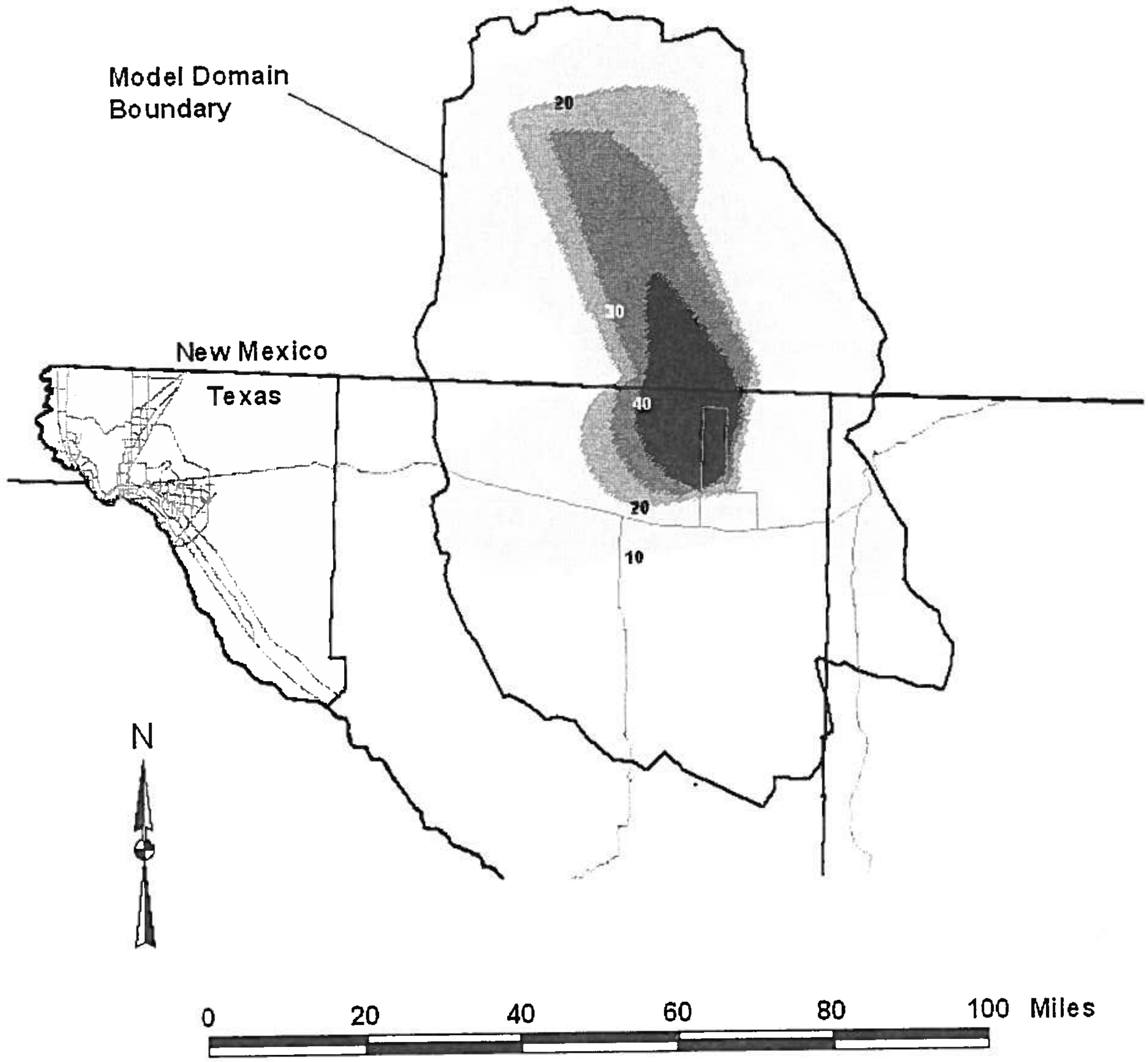


Figure 110. Drawdown (ft) due to Groundwater Pumping from 1948 to 2002
Hybrid Model

8.0 SIMULATION OF POTENTIAL FUTURE CONDITIONS

The models were used to simulate potential future conditions by examining two key variables: alternative climatic conditions and alternative pumping scenarios. The objective of the simulations was to develop an understanding of groundwater yields within the new boundaries of the Hudspeth County Underground Water Conservation District No. 1 (HCUWCD). The alternative climatic conditions were based on a series of 50-year simulations that were derived from a tree-ring data set for New Mexico (and Arizona) that covers the years 1000 to 1988 (Ni and others, 2002). The alternative pumping scenarios were based on the HCUWCD rules and variations on those rules for the purposes of understanding the sensitivity of relaxation or tightening of the regulations. These simulations were run to develop information related to groundwater elevation changes under various pumping scenarios, not to suggest or recommend changes to those rules.

Since the focus of the simulations focuses on HCUWCD, a review of key sections of the management plan and rules is presented, followed by a description of the development of the climatic scenarios. Finally, the results of the simulations are presented.

8.1 Hudspeth County Underground Water Conservation District No. 1

The Hudspeth County Underground Water Conservation District No. 1 was created on December 31, 1956. The current management plan was updated in 2007, and the current rules were updated in 2005. The key elements of the management plan and rules are the explicit management of groundwater on a sustainable basis, and the use of a historic period to grant permits to users.

The rules of the District outline a permitting system that has resulted in limitations that were designed to achieve the sustainable pumping goals of the management plan. Three types of permits are granted:

1. Validation permits are granted for existing and historic uses.
2. Operating permits are granted for pumping where no validation permit exists.
3. Transfer permits are granted for uses outside the District boundaries, and require either a validation permit or an operating permit prior to issuance.

For irrigation uses (by far the largest use of water), validation permits were issued for acres of "Existing and Historic Irrigated Land" determined to have been irrigated at least one year during the "Existing and Historic Use Period" (1992 to 2002). The water use on these lands is then calculated by multiplying the validated acreage by the "Water Allocation" which is determined on an acre-foot per acre basis. The 2007 Management Plan stated that approximately 34,000 acres of land has been issued validation permits.

The "Water Allocation" is the quantity of groundwater that can be pumped each year and is adjusted every two years based on the groundwater elevation in a single monitoring well (Well 48-07-516). The District Board determines a "two-year moving average of monthly water surface elevations" on January 31 of each odd numbered year. For validation permits for irrigation, "Water Allocation" limits are applied based on the groundwater level in the single monitoring well as shown in Table 45.

Table 45. Water Allocation Limits for Pumping in HCUWCD

Groundwater Elevation in Well 48-07-516 (two-year moving average)	Water Allocation
> 3570 ft	4.0 AF/acre/yr
3560 to 3570	Pro-rata allocation between 3.0 and 4.0 AF/acre/yr
< 3560	3.0 AF/acre/yr

Note that the Water Allocation Limits are for total pumping. Simulations using the groundwater models from this investigation require estimates of consumptive or net pumping. The 2007 Management Plan assumes that net pumping can be calculated after accounting for the "leaching fraction" of 30%. Therefore, when the full Water Allocation Limit of 4 AF/acre/yr is in effect, the net pumping rate would be:

4.0 AF/ac/yr * (1-0.3) = 2.8 AF/ac/yr

When the minimum Water Allocation Limit is in effect, the net pumping rate would be:

3.0 AF/ac/yr * (1-0.3) = 2.1 AF/ac/yr

This net pumping rate would be available for transfer under a transfer permit as provided in the current rules. Assuming that the maximum Water Allocation Limit was in effect, the maximum net pumping would be:

2.8 AF/acre/yr * 34,000 acres = 95,200 AF/yr

If the minimum Water Allocation Limit was in effect, the maximum net pumping would be:

2.1 AF/acre/yr * 34,000 acres = 71,400 AF/yr

As can be seen, these pumping maxima are based on the assumption that all permitted acreage is irrigated. However, individual permit holders are allowed to fallow land and apply that water to other irrigated land. Note that from 1995 to 2002, actual irrigated acreage ranges (estimated from this analysis) range from about 17,500 acres to about 22,000 acres. HCUWCD estimated that irrigated acreage within the boundaries of HCUWCD was 22,550 in the year 2000. Using the HCUWCD estimate for the year 2000, about 66% of the permitted land was actually irrigated. Therefore, the actual duty applied to irrigated land (as opposed to the duty for permitted land) is effectively higher than what appears in the HCUWCD rules. This would raise the maximum total pumping duty to 6.03 AF/acre/yr, and the net pumping duty to 4.22 AF/acre/yr.

Simulations of potential future conditions were based on 2001 acreages and the application of "corrected" duties to reflect the actual practice of fallowing land and applying the savings to other irrigated land.

8.2 Pumping Scenarios

Fifteen pumping scenarios were developed for use in the future simulations. Three scenarios were based on a constant pumping amount without regard to the groundwater elevation in any well, and 12 scenarios were based on pumping that was linked to the groundwater elevation of Well 48-07-516. Of the 12 scenarios that were based on pumping linked to the groundwater elevation of Well 48-07-516, 8 used the elevation control (to the nearest foot) in the rules (Table 42), two used increased control elevations (2 feet and 4 feet, respectively), and two used decreased control elevations (2 feet and 4 feet, respectively). In addition, a simulation that assumed zero pumping was used as a control.

Table 46 presents a summary of pumping scenarios 1 to 6 (P1 to P6). P1 represents the maximum corrected HCUWCD duty, applied without regard to the groundwater elevation in Well 48-07-516. P2 represents application of a duty that would result in 2001 pumping (108,000 AF/yr), without regard to the groundwater elevation in Well 48-07-516. P3 represents an increase in pumping that would result in a constant pumping of about 123,000 AF/yr. P4 represents a simulation of HCUWCD rules with corrected factors to reflect the fallowed land percentage of 2001. Note that the pro-rata decline in duty between groundwater elevations of 3570 ft and 3560 ft are estimated to the nearest foot. It is unclear in the HCUWCD rules if this is correct, or the pro-rata calculation would be made at intervals at less than a foot. P5 represents a simulation of a duty that would result in 2001 pumping (108,000 AF/yr) at the maximum duty (4.83 AF/acre/yr), and would be reduced if the groundwater elevation in Well 48-07-516 dropped below 3570 ft. Finally, P6 represents an increase in duties, with a reduction if the groundwater elevation in Well 48-07-516 dropped below 3570 ft.

Table 46. Summary of Pumping Scenarios P1 to P6
All Duties in AF/acre/yr

2-Year Average Groundwater Elevation in Well 48-07-516	P1 ("Corrected" HCUWCD Duties)	P2 ("Historic" Duties - 2001 Conditions)	P3 (High Duties)	P4 ("Corrected" HCUWCD Duties)	P5 ("Historic" Duties - 2001 Conditions)	P6 (High Duties)
3570	4.22	4.83	5.44	4.22	4.83	5.44
3569				4.12	4.72	5.33
3568				4.01	4.62	5.23
3567				3.91	4.51	5.12
3566				3.80	4.41	5.02
3565				3.69	4.30	4.91
3564				3.59	4.20	4.81
3563				3.48	4.09	4.70
3562				3.38	3.99	4.60
3561				3.27	3.88	4.49
3560				3.17	3.77	4.38

Note that in P4 to P6, pumping amounts are set based on a two-year average of groundwater elevation in Well 48-07-516. HCUWCD rules call for a determination to be made every other year (odd years). Therefore, the simulations were run for two years, an average of the groundwater elevation was taken for the cell in which Well 48-07-516 is located, and pumping for the subsequent two years was specified based on the limits in Table 43.

Table 47 summarizes pumping scenarios 7 to 10 (P7 to P10). These scenarios were developed to understand the sensitivity in the HCUWCD assigned elevations for Well 48-07-516. These simulations use the corrected HCUWCD duties of P4 and raise and lower the elevation controls 2 and 4 feet.

Table 47. Summary of Pumping Scenarios P7 to P10
All Duties in AF/acre/yr

P7		P8		P9		P10	
2-Year Average Groundwater Elevation in Well 48-07-516 (HCUWCD - 2)	"Corrected" HCUWCD Duties	2-Year Average Groundwater Elevation in Well 48-07-516 (HCUWCD - 4)	"Corrected" HCUWCD Duties	2-Year Average Groundwater Elevation in Well 48-07-516 (HCUWCD + 2)	"Corrected" HCUWCD Duties	2-Year Average Groundwater Elevation in Well 48-07-516 (HCUWCD + 4)	"Corrected" HCUWCD Duties
3568	4.22	3566	4.22	3572	4.22	3574	4.22
3567	4.12	3565	4.12	3571	4.12	3573	4.12
3566	4.01	3564	4.01	3570	4.01	3572	4.01
3565	3.91	3563	3.91	3569	3.91	3561	3.91
3564	3.8	3562	3.8	3568	3.80	3570	3.8
3563	3.69	3561	3.69	3567	3.69	3569	3.69
3562	3.59	3560	3.59	3566	3.59	3568	3.59
3561	3.48	3559	3.48	3565	3.48	3567	3.48
3560	3.38	3558	3.38	3564	3.38	3566	3.38
3559	3.27	3557	3.27	3563	3.27	3565	3.27
3558	3.17	3556	3.17	3562	3.17	3564	3.17

After evaluating the initial results of P1 to P10, additional simulations were developed that looked at decreasing the pumping to provide a wide range of conditions for evaluation. Table 48 presents these pumping scenarios (P11 to P15). These scenarios use the HCUWCD groundwater elevation controls from Well 48-07-516 to reduce the duties in a fashion similar to P4 to P10.

Table 48. Summary of Pumping Scenarios P11 to P15
All Duties in AF/acre/yr

2-Year Average Groundwater Elevation in Well 48-07-516	P11 (Maximum Duty = 1.17)	P12 (Maximum Duty = 1.78)	P13 (Maximum Duty = 2.39)	P14 (Maximum Duty = 3.00)	P15 (Maximum Duty = 3.61)
3570	1.17	1.78	2.39	3.00	3.61
3569	1.06	1.67	2.28	2.89	3.50
3568	0.96	1.57	2.18	2.79	3.40
3567	0.85	1.46	2.07	2.68	3.29
3566	0.75	1.36	1.97	2.58	3.19
3565	0.64	1.25	1.86	2.47	3.08
3564	0.54	1.15	1.76	2.37	2.98
3563	0.43	1.04	1.65	2.26	2.87
3562	0.33	0.94	1.55	2.16	2.77
3561	0.22	0.83	1.44	2.05	2.66
3560	0.11	0.72	1.33	1.94	2.55

Figure 111 summarizes the maximum and minimum annual pumping associated with each scenario based on the maximum duty listed in Tables 43 to 45. Note that the pumping in the simulations ranged from 0 to about 120,000 AF/yr. This range provided the needed data to evaluate groundwater yields of the area.

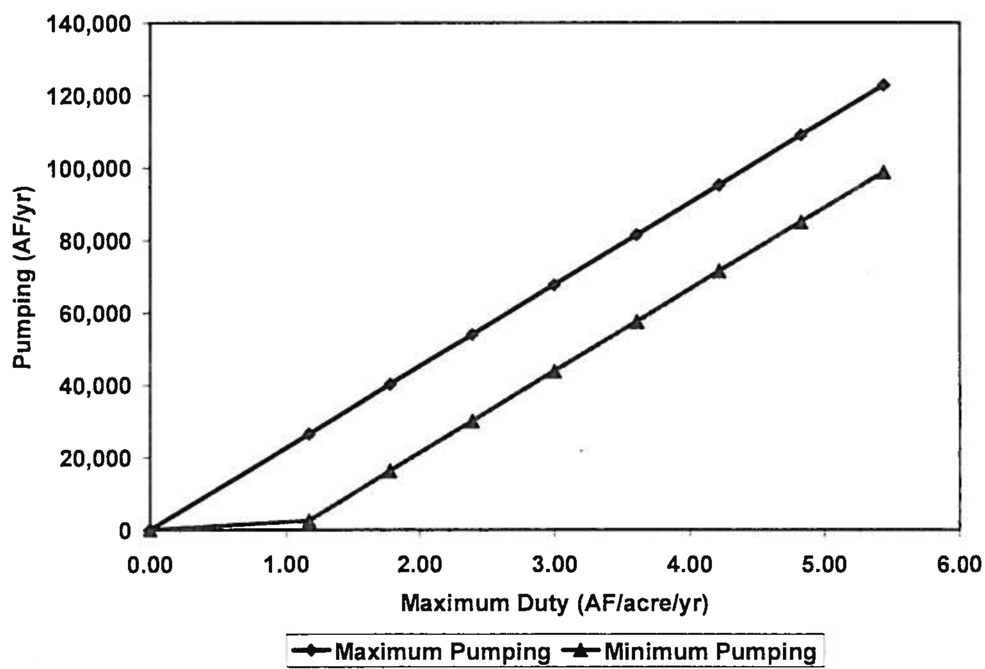


Figure 111. Summary of Minimum and Maximum Annual Pumping Used in Simulations

8.3 Climatic Scenarios

A common challenge in the simulation of future conditions is the selection of future climatic conditions that drive potential future recharge conditions. In the case of this analysis, recharge is driven largely by precipitation, and, as described in Section 6.3.8, an annual precipitation factor was used simulate variations in recharge during the calibration period. Methods commonly applied include using the same sequence as the calibration period, or simulating a constant average or dry condition throughout the entire future simulation period. Due to the nature of the pumping scenarios that are related to the HCUWCD rules (i.e. decreasing pumping with decreasing groundwater elevations in Well 48-07-516), neither of these approaches was particularly appealing.

Ni and others (2002) published a study that resulted in the estimation of "cool-season" precipitation in Arizona and New Mexico from the year 1000 to the year 1988, for a 988-year record of precipitation estimates, using 19 tree-ring chronologies in the southwestern United States. Since most of the precipitation and hence recharge is in the upper elevations of the Sacramento Mountains in New Mexico, this dataset was viewed as useful to "drive" the recharge portion of the simulations. Figure 112 presents the zones used by Ni and others (2002) for New Mexico, and includes the model domain. It can be seen that the model domain lies within Zones 6, 7 and 8.

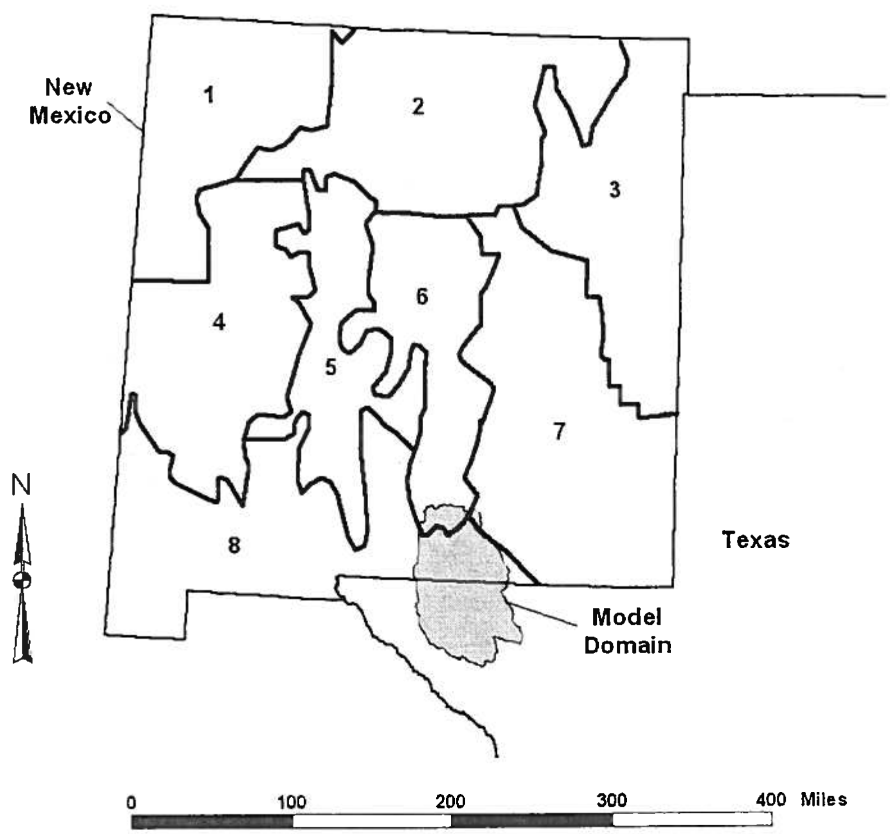


Figure 112. New Mexico Climate Zones used by Ni and others (2002)

The data for Zones 6, 7 and 8 from Ni and others (2002) was averaged and summarized as annual estimates and estimates of the running 50-year average in Figure 113. The running 50-year average is presented alone in Figure 114.

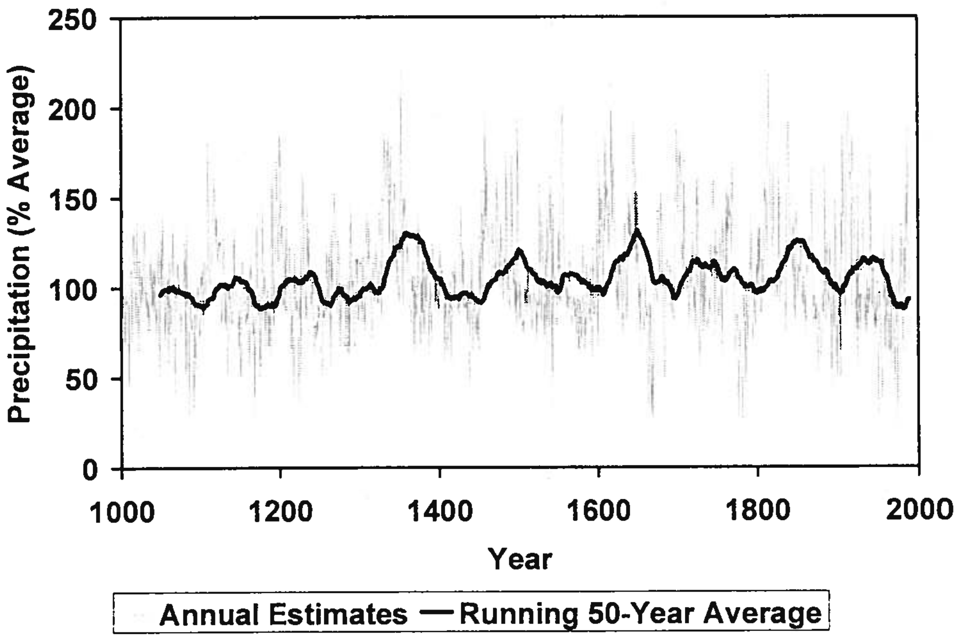


Figure 113. New Mexico Zones 6, 7 and 8 Precipitation Estimates from Ni and others (2002)

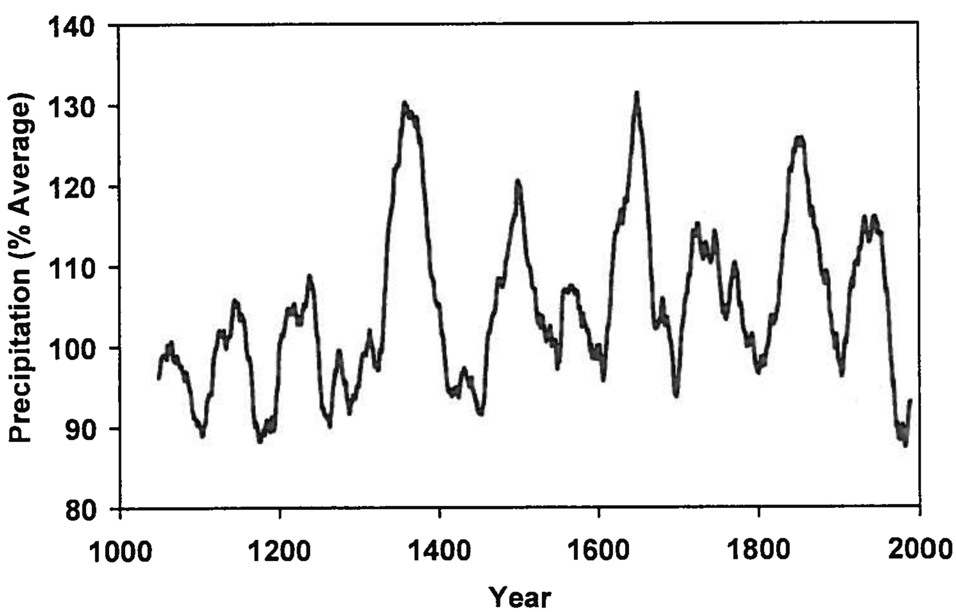


Figure 114. New Mexico Zones 6, 7 and 8 Precipitation Estimates from Ni and others (2002)
Running 50-Year Average

Based on the running 50-year average, the most severe dry period occurred from the early 1930s to the early 1980s, which covers most of the period of development and the calibration period of the model. Also note that 50-year averages of precipitation range from just below 90% of average to about 130% of average. Based on the running 50-year average, significant wet periods that have lasted for decades have been typically followed by significant dry periods that have lasted for decades over the last 1000 years. Conversely, significant dry periods that have lasted for decades have typically been followed by significant wet periods that have lasted for decades. Based on data from Ni and others (2002), there is some suggestion that the area is entering a rising precipitation period, where 50-year average in rainfall would be expected to increase for the next several decades. Extrapolation of this type of trend, however, is highly speculative and, at best, tenuous.

Recent precipitation records in the area (reproduced in the annual precipitation factors that were used during the calibration period) are presented in Figure 115. Note that from the early 1950s, precipitation was generally increasing until the late 1990s. Both relative minima and maxima were increasing during that time period, which are generally consistent with the long-term trend suggested by the data of Ni and others (2002).

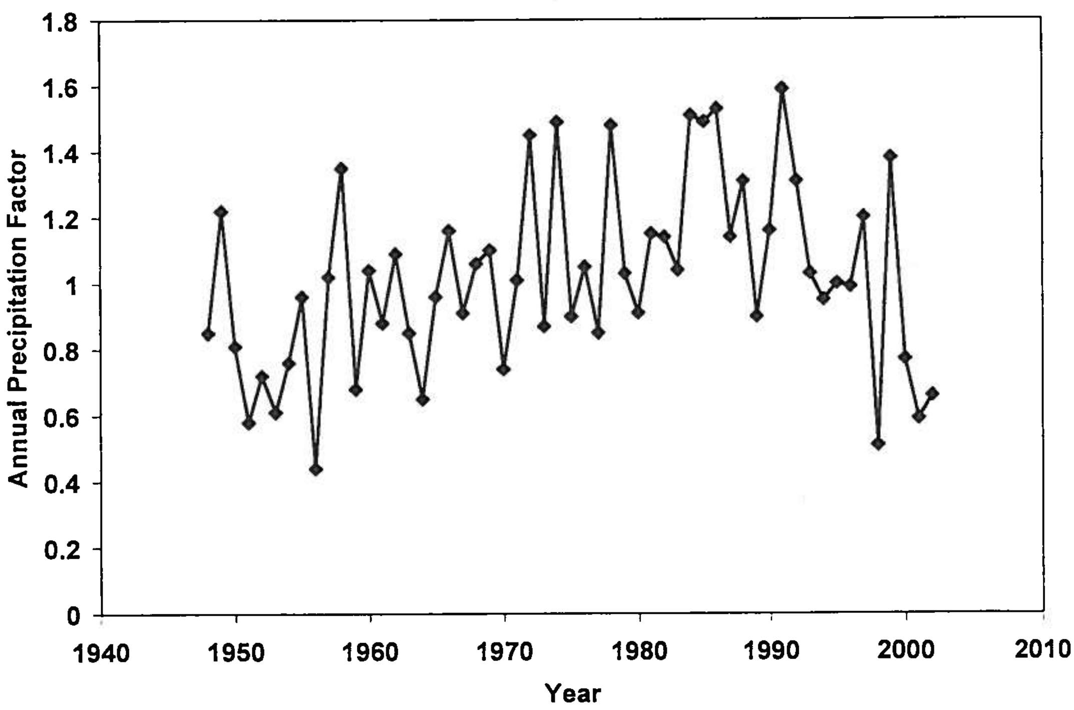


Figure 115. Annual Precipitation Factors used During Calibration Period

The running 50-year averages from the dataset developed by Ni and others (2002) were further evaluated by calculating the running 50-year standard deviation for each 50-year period. The plot of running 50-year average vs. running 50-year standard deviation is presented in Figure 116. Note that wetter periods are typically more variable (higher standard deviation), and drier period are typically less variable (lower standard deviation).

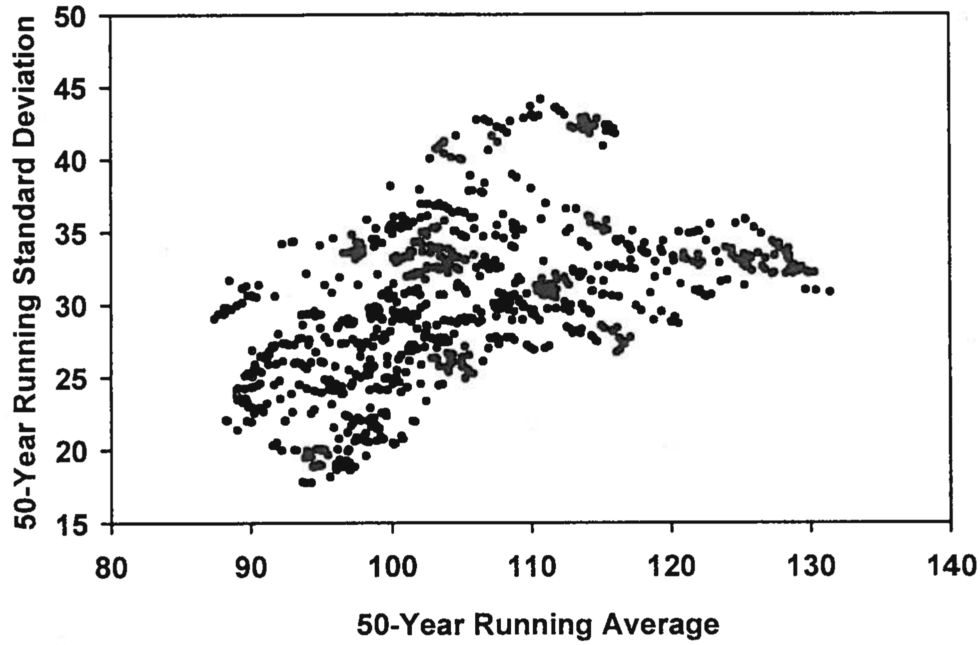


Figure 116. Running 50-Year Average (% of Average) vs. Running 50-Year Standard Deviation from Dataset of Ni and others (2002)

The data from Figure 116 were used to develop seven climatic scenarios used in the simulations: 1) driest, 2) wettest, 3) lowest standard deviation, 4) highest standard deviation, 5) average with low standard deviation, 6) average with intermediate standard deviation, and 7) average with high standard deviation. These seven climatic scenarios are summarized in Table 49.

Table 49. Summary of Seven Climatic Scenarios Developed from dataset of Ni and others (2002)

Scenario Number	Scenario Description	Precipitation (% Average)	Standard Deviation	Period
C1	Driest	87	29	1933 to 1982
C2	Wettest	131	31	1602 to 1651
C3	Lowest Standard Deviation	94	18	1377 to 1426
C4	Highest Standard Deviation	111	44	1907 to 1956
C5	Average - Low Standard Deviation	100	20	1015 to 1064
C6	Average - Intermediate Standard Deviation	100	28	1562 to 1611
C7	Average - High Standard Deviation	100	38	1915 to 1964

8.4 Summary of All Simulations

The three models, 16 pumping scenarios (including the scenario with zero pumping) and 7 climatic scenarios were used to develop 336 simulations. Recall that the southern boundary of the model used a decreasing boundary head during the calibration. Because it is unknown whether the same rate of decline would continue into the future, two sets of assumptions were applied to the future simulations: one set of 336 simulations were run assuming the same rate of decline, and one set of 336 simulations where the 2002 boundary heads are held constant. Therefore, a total of 772 simulations were run. Each simulation was run for 50 years, and the heads at the end of 2002 were used to initiate the solution.

Table 50 summarizes the basic scenarios (model, pumping scenarios and climatic scenarios). Table 51 details each of the 336 simulations by code used in Table 50.

Table 50. Summary of Scenario Codes for Simulation Details in Table 51

Model Scenario Code	Scenario Description
M1	Structural Geology
M2	Isotope Geochemistry
M3	Hybrid

Pumping Scenario Code	Scenario Description
P1	Constant Pumping - "Corrected" HCUWCD Duty
P2	Constant Pumping - Historic Duties (2001 Conditions)
P3	Constant Pumping - High Duties
P4	Decreasing Pumping - "Corrected" HCUWCD Duty
P5	Decreasing Pumping - Historic Duties (2001 Conditions)
P6	Decreasing Pumping - High Duties
P7	Decreasing Pumping - "Corrected" HCUWCD Duty, Elevation Control -2 feet
P8	Decreasing Pumping - "Corrected" HCUWCD Duty, Elevation Control -4 feet
P9	Decreasing Pumping - "Corrected" HCUWCD Duty, Elevation Control +2 feet
P10	Decreasing Pumping - "Corrected" HCUWCD Duty, Elevation Control +4 feet
P11	Decreasing Pumping - Maximum Duty = 1.17 AF/acre/year
P12	Decreasing Pumping - Maximum Duty = 1.78 AF/acre/year
P13	Decreasing Pumping - Maximum Duty = 2.39 AF/acre/year
P14	Decreasing Pumping - Maximum Duty = 3.00 AF/acre/year
P15	Decreasing Pumping - Maximum Duty = 3.61 AF/acre/year

Climatic Scenario Code	Scenario Description
C1	Driest
C2	Wettest
C3	Lowest Standard Deviation
C4	Highest Standard Deviation
C5	Average - Low Standard Deviation
C6	Average - Intermediate Standard Deviation
C7	Average - High Standard Deviation

Table 51. Details of Simulations – Page 1 of 4
(Codes detailed in Table 50)

Simulation	Model	Climate	Pumping
1	M1	C1	P1
2	M2	C1	P1
3	M3	C1	P1
4	M1	C2	P1
5	M2	C2	P1
6	M3	C2	P1
7	M1	C3	P1
8	M2	C3	P1
9	M3	C3	P1
10	M1	C4	P1
11	M2	C4	P1
12	M3	C4	P1
13	M1	C5	P1
14	M2	C5	P1
15	M3	C5	P1
16	M1	C6	P1
17	M2	C6	P1
18	M3	C6	P1
19	M1	C7	P1
20	M2	C7	P1
21	M3	C7	P1
22	M1	C1	P2
23	M2	C1	P2
24	M3	C1	P2
25	M1	C2	P2
26	M2	C2	P2
27	M3	C2	P2
28	M1	C3	P2
29	M2	C3	P2
30	M3	C3	P2
31	M1	C4	P2
32	M2	C4	P2
33	M3	C4	P2
34	M1	C5	P2
35	M2	C5	P2
36	M3	C5	P2
37	M1	C6	P2
38	M2	C6	P2
39	M3	C6	P2
40	M1	C7	P2
41	M2	C7	P2
42	M3	C7	P2
43	M1	C1	P3
44	M2	C1	P3
45	M3	C1	P3
46	M1	C2	P3
47	M2	C2	P3
48	M3	C2	P3
49	M1	C3	P3
50	M2	C3	P3
51	M3	C3	P3
52	M1	C4	P3
53	M2	C4	P3
54	M3	C4	P3
55	M1	C5	P3
56	M2	C5	P3
57	M3	C5	P3
58	M1	C6	P3
59	M2	C6	P3
60	M3	C6	P3
61	M1	C7	P3
62	M2	C7	P3
63	M3	C7	P3
64	M1	C1	P4
65	M2	C1	P4
66	M3	C1	P4
67	M1	C2	P4
68	M2	C2	P4
69	M3	C2	P4
70	M1	C3	P4
71	M2	C3	P4
72	M3	C3	P4
73	M1	C4	P4
74	M2	C4	P4
75	M3	C4	P4
76	M1	C5	P4
77	M2	C5	P4
78	M3	C5	P4
79	M1	C6	P4
80	M2	C6	P4
81	M3	C6	P4
82	M1	C7	P4
83	M2	C7	P4
84	M3	C7	P4
85	M1	C1	P5
86	M2	C1	P5
87	M3	C1	P5
88	M1	C2	P5
89	M2	C2	P5
90	M3	C2	P5

Table 51. Details of Simulations – Page 2 of 4
(Codes detailed in Table 50)

Simulation	Model	Climate	Pumping
91	M1	C3	P5
92	M2	C3	P5
93	M3	C3	P5
94	M1	C4	P5
95	M2	C4	P5
96	M3	C4	P5
97	M1	C5	P5
98	M2	C5	P5
99	M3	C5	P5
100	M1	C6	P5
101	M2	C6	P5
102	M3	C6	P5
103	M1	C7	P5
104	M2	C7	P5
105	M3	C7	P5
106	M1	C1	P6
107	M2	C1	P6
108	M3	C1	P6
109	M1	C2	P6
110	M2	C2	P6
111	M3	C2	P6
112	M1	C3	P6
113	M2	C3	P6
114	M3	C3	P6
115	M1	C4	P6
116	M2	C4	P6
117	M3	C4	P6
118	M1	C5	P6
119	M2	C5	P6
120	M3	C5	P6
121	M1	C6	P6
122	M2	C6	P6
123	M3	C6	P6
124	M1	C7	P6
125	M2	C7	P6
126	M3	C7	P6
127	M1	C1	P7
128	M2	C1	P7
129	M3	C1	P7
130	M1	C2	P7
131	M2	C2	P7
132	M3	C2	P7
133	M1	C3	P7
134	M2	C3	P7
135	M3	C3	P7

Simulation	Model	Climate	Pumping
136	M1	C4	P7
137	M2	C4	P7
138	M3	C4	P7
139	M1	C5	P7
140	M2	C5	P7
141	M3	C5	P7
142	M1	C6	P7
143	M2	C6	P7
144	M3	C6	P7
145	M1	C7	P7
146	M2	C7	P7
147	M3	C7	P7
148	M1	C1	P8
149	M2	C1	P8
150	M3	C1	P8
151	M1	C2	P8
152	M2	C2	P8
153	M3	C2	P8
154	M1	C3	P8
155	M2	C3	P8
156	M3	C3	P8
157	M1	C4	P8
158	M2	C4	P8
159	M3	C4	P8
160	M1	C5	P8
161	M2	C5	P8
162	M3	C5	P8
163	M1	C6	P8
164	M2	C6	P8
165	M3	C6	P8
166	M1	C7	P8
167	M2	C7	P8
168	M3	C7	P8
169	M1	C1	P9
170	M2	C1	P9
171	M3	C1	P9
172	M1	C2	P9
173	M2	C2	P9
174	M3	C2	P9
175	M1	C3	P9
176	M2	C3	P9
177	M3	C3	P9
178	M1	C4	P9
179	M2	C4	P9
180	M3	C4	P9

Table 51. Details of Simulations – Page 3 of 4
(Codes detailed in Table 50)

Simulation	Model	Climate	Pumping
181	M1	C5	P9
182	M2	C5	P9
183	M3	C5	P9
184	M1	C6	P9
185	M2	C6	P9
186	M3	C6	P9
187	M1	C7	P9
188	M2	C7	P9
189	M3	C7	P9
190	M1	C1	P10
191	M2	C1	P10
192	M3	C1	P10
193	M1	C2	P10
194	M2	C2	P10
195	M3	C2	P10
196	M1	C3	P10
197	M2	C3	P10
198	M3	C3	P10
199	M1	C4	P10
200	M2	C4	P10
201	M3	C4	P10
202	M1	C5	P10
203	M2	C5	P10
204	M3	C5	P10
205	M1	C6	P10
206	M2	C6	P10
207	M3	C6	P10
208	M1	C7	P10
209	M2	C7	P10
210	M3	C7	P10
211	M1	C1	Zero
212	M2	C1	Zero
213	M3	C1	Zero
214	M1	C2	Zero
215	M2	C2	Zero
216	M3	C2	Zero
217	M1	C3	Zero
218	M2	C3	Zero
219	M3	C3	Zero
220	M1	C4	Zero
221	M2	C4	Zero
222	M3	C4	Zero
223	M1	C5	Zero
224	M2	C5	Zero
225	M3	C5	Zero

Simulation	Model	Climate	Pumping
226	M1	C6	Zero
227	M2	C6	Zero
228	M3	C6	Zero
229	M1	C7	Zero
230	M2	C7	Zero
231	M3	C7	Zero
232	M1	C1	P11
233	M2	C1	P11
234	M3	C1	P11
235	M1	C2	P11
236	M2	C2	P11
237	M3	C2	P11
238	M1	C3	P11
239	M2	C3	P11
240	M3	C3	P11
241	M1	C4	P11
242	M2	C4	P11
243	M3	C4	P11
244	M1	C5	P11
245	M2	C5	P11
246	M3	C5	P11
247	M1	C6	P11
248	M2	C6	P11
249	M3	C6	P11
250	M1	C7	P11
251	M2	C7	P11
252	M3	C7	P11
253	M1	C1	P12
254	M2	C1	P12
255	M3	C1	P12
256	M1	C2	P12
257	M2	C2	P12
258	M3	C2	P12
259	M1	C3	P12
260	M2	C3	P12
261	M3	C3	P12
262	M1	C4	P12
263	M2	C4	P12
264	M3	C4	P12
265	M1	C5	P12
266	M2	C5	P12
267	M3	C5	P12
268	M1	C6	P12
269	M2	C6	P12
270	M3	C6	P12

Table 51. Details of Simulations – Page 4 of 4
(Codes detailed in Table 50)

Simulation	Model	Climate	Pumping
271	M1	C7	P12
272	M2	C7	P12
273	M3	C7	P12
274	M1	C1	P13
275	M2	C1	P13
276	M3	C1	P13
277	M1	C2	P13
278	M2	C2	P13
279	M3	C2	P13
280	M1	C3	P13
281	M2	C3	P13
282	M3	C3	P13
283	M1	C4	P13
284	M2	C4	P13
285	M3	C4	P13
286	M1	C5	P13
287	M2	C5	P13
288	M3	C5	P13
289	M1	C6	P13
290	M2	C6	P13
291	M3	C6	P13
292	M1	C7	P13
293	M2	C7	P13
294	M3	C7	P13
295	M1	C1	P14
296	M2	C1	P14
297	M3	C1	P14
298	M1	C2	P14
299	M2	C2	P14
300	M3	C2	P14
301	M1	C3	P14
302	M2	C3	P14
303	M3	C3	P14

Simulation	Model	Climate	Pumping
304	M1	C4	P14
305	M2	C4	P14
306	M3	C4	P14
307	M1	C5	P14
308	M2	C5	P14
309	M3	C5	P14
310	M1	C6	P14
311	M2	C6	P14
312	M3	C6	P14
313	M1	C7	P14
314	M2	C7	P14
315	M3	C7	P14
316	M1	C1	P15
317	M2	C1	P15
318	M3	C1	P15
319	M1	C2	P15
320	M2	C2	P15
321	M3	C2	P15
322	M1	C3	P15
323	M2	C3	P15
324	M3	C3	P15
325	M1	C4	P15
326	M2	C4	P15
327	M3	C4	P15
328	M1	C5	P15
329	M2	C5	P15
330	M3	C5	P15
331	M1	C6	P15
332	M2	C6	P15
333	M3	C6	P15
334	M1	C7	P15
335	M2	C7	P15
336	M3	C7	P15

8.5 Simulation Results

The results of the simulation demonstrated that the two alternative southern boundary heads made no significant difference to groundwater elevation changes or groundwater budget components in the Dell City area. Therefore, only the results from the decreasing southern boundary are presented in this section.

Subregional groundwater budgets were developed of all simulations, and the average values for each of the 336 50-year run for the new HCUWCD zone (previously presented as Figure 99) were compiled and presented in Appendix D. Impacts to various components as a result of pumping are described in this section, as well as changes to groundwater elevations.

Figure 117 presents groundwater pumping vs. inflow from New Mexico for the new HCUWCD zone. Note that the results are categorized by the three models. Note that the flows across the state line increase with increased pumping, suggesting that the pumping is inducing this additional flow. The observed vertical spreads for individual models is due to varying climatic, or recharge conditions. Also note that the structural geology model estimates higher flow rates and the increases are greater than the other two models. This is consistent with the findings of the 1948 to 2002 calibration period results related to the higher total inflow results of the structural geology model, and agree with the conceptualization of Mayer (1995).

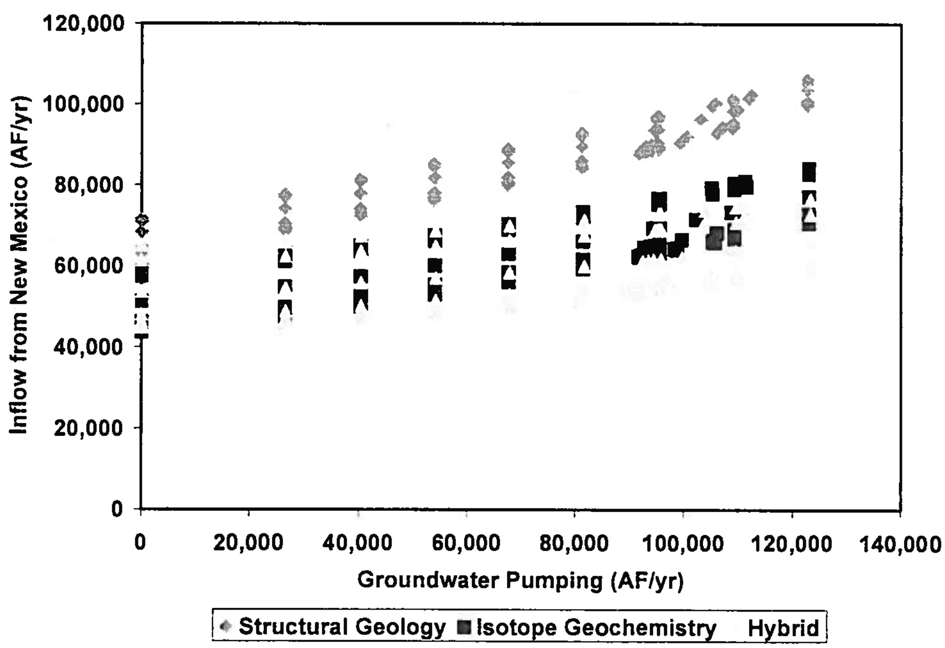


Figure 117. Simulation Results for the New HCUWCD Zone
Groundwater Pumping vs. Inflow from New Mexico

Figure 118 presents groundwater pumping vs. inflow from the Diablo Plateau for the new HCUWCD zone. Note that the results are categorized by the three models. Note that the flows across the southwestern boundary of HCUWCD (Diablo Plateau) increase with increased pumping, suggesting that the pumping is inducing this additional flow. The observed vertical spreads for individual models is due to varying climatic, or recharge conditions. In contrast to the flow from New Mexico, the structural geology model exhibits the lowest flow rate and the smallest increase due to increased pumping. The isotope geochemistry model exhibits the largest inflow and the largest increase as a result of pumping, which is consistent with the results of the 1948 to 2002 calibration period results and the findings of Eastoe and Hibbs (2005). Finally, the hybrid model exhibits a flow rate and increase in flow rate due to pumping that is higher than the structural geology model, but less than the isotope geochemistry model. The intent of the development of the hybrid model was to establish an intermediate conceptualization between those of Mayer (1995) and Eastoe and Hibbs (2005).

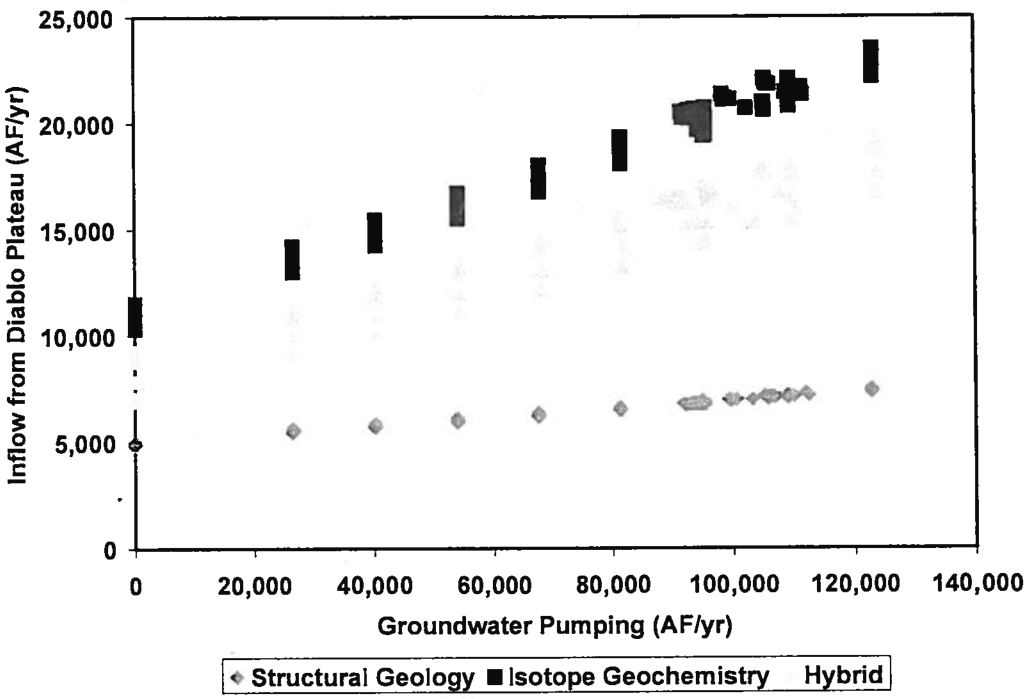


Figure 118. Simulation Results for the New HCUWCD Zone Groundwater Pumping vs. Inflow from the Diablo Plateau

Figure 119 presents groundwater pumping vs. inflow from the eastern boundary of the new HCUWCD for the new HCUWCD zone. Note that the results are categorized by the three models. Note that the flows across the eastern boundary of HCUWCD increase with increased pumping, suggesting that the pumping is inducing this additional flow. The observed vertical spreads for individual models is due to varying climatic, or recharge conditions. The amount and increases in flows across the eastern boundary are significantly less than those for the flow from New Mexico and the flow from Diablo Plateau. Generally, the flows in the isotope geochemistry model are lowest and the structural geology and hybrid models are nearly the same.

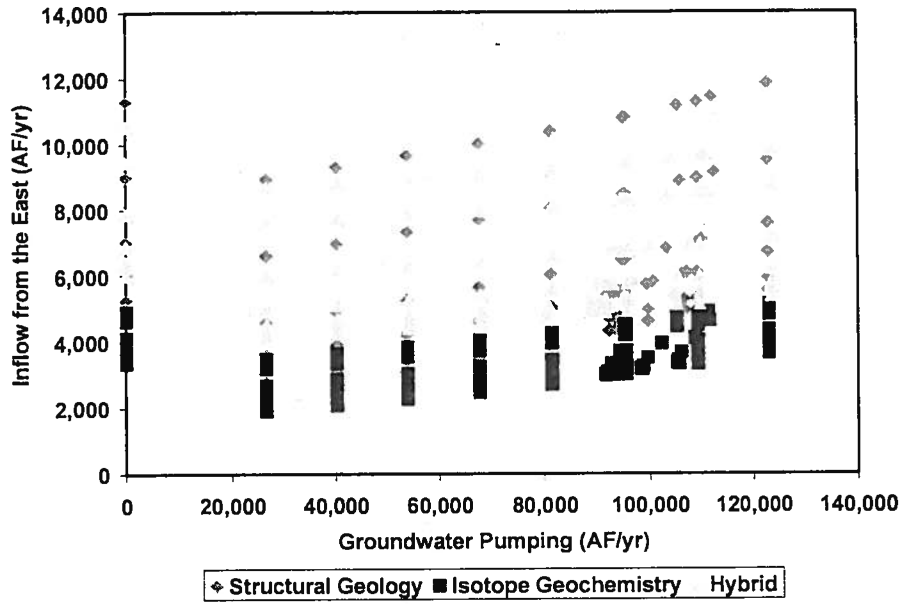


Figure 119. Simulation Results for the New HCUWCD Zone
Groundwater Pumping vs. Inflow across the Eastern Boundary of HCUWCD

Figure 120 presents groundwater pumping vs. evapotranspiration within the new boundaries of the HCUWCD. Note that evapotranspiration decreases with increased pumping, which suggests that this component of natural outflow is captured by the increased pumping. The observed vertical spreads for individual models is due to varying climatic, or recharge conditions.

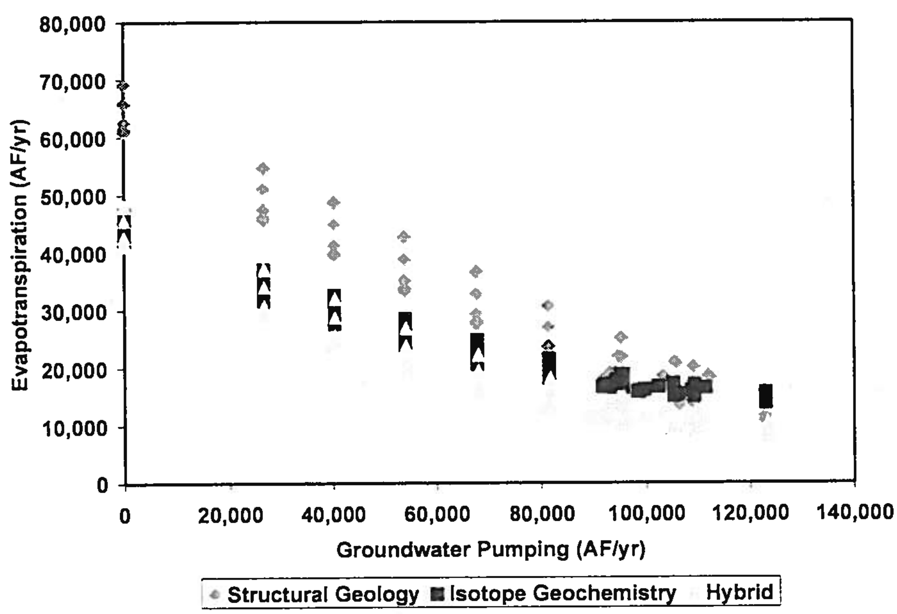


Figure 120. Simulation Results for the New HCUWCD Zone
Groundwater Pumping vs. Evapotranspiration within HCUWCD

The highest evapotranspiration, and the largest decrease with increased pumping, was estimated by the structural geology model. This is consistent with the 1948 to 2002 calibration period results that suggested that the inflow and outflow were higher in the structural geology model than in the other two models. Note that at high pumping (over 120,000 AF/yr), the estimated rate of evapotranspiration in all three models is below 20,000 AF/yr.

Figure 121 presents groundwater pumping vs. groundwater storage change within the new boundaries of the HCUWCD. At zero pumping, the groundwater storage increase ranges from about 12,000 AF/yr to about 35,000 AF/yr. The range is attributable to alternative climatic (or recharge) scenarios. At the other extreme, pumping over 120,000 AF/yr would result in a storage decline of between about 10,000 AF/yr to about 50,000 AF/yr, depending on climatic conditions. For pumping scenarios above about 54,000 AF/yr, groundwater storage would decline; pumping less than about 54,000 AF/yr would generally result in groundwater storage increases.

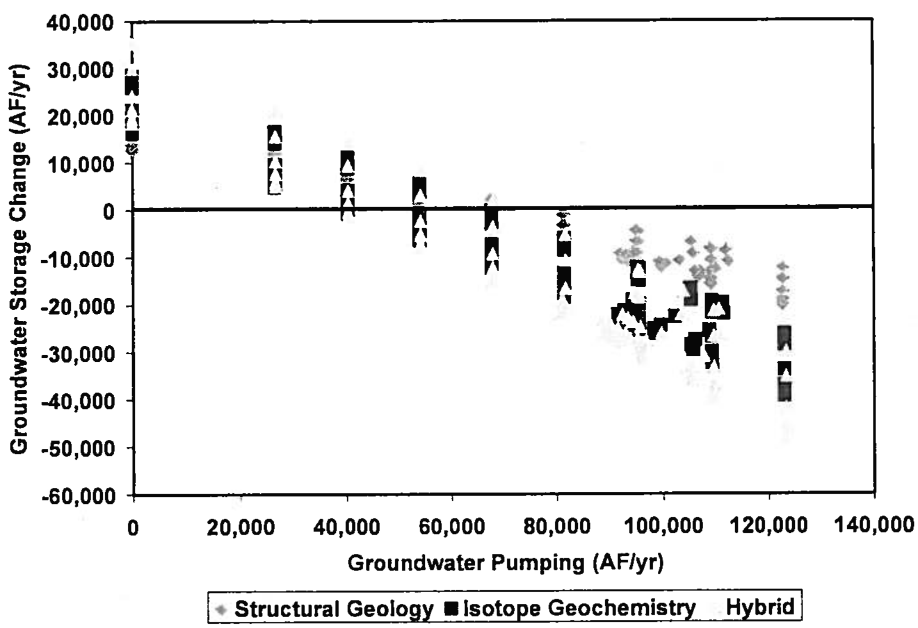


Figure 121. Simulation Results for the New HCUWCD Zone
Groundwater Pumping vs. Groundwater Storage Change within HCUWCD

The observed vertical spreads for individual models is due to varying climatic, or recharge conditions. The ranges are consistent with observed conditions from 1948 to 2002. Recall that groundwater elevations dropped after the start of irrigation pumping in 1948. Since the 1980s, groundwater elevations have essentially stabilized due to the combined effect of decreased pumping and increased recharge.

Note that the structural geology model exhibits less groundwater storage decline due to pumping than the other two models. This is apparently due to the higher induced inflow from New Mexico and reduced evapotranspiration. These "captured" flows result in less drawdown than the other models.

The impact of the climatic scenarios is evaluated further by examining the pumping vs. groundwater storage decline relationship for each of the climatic scenarios. Figure 122 presents the simulations that included the driest conditions, about 87% of average precipitation for the entire 50-year simulation. Note that under these climatic conditions, storage change is zero when pumping is about 40,000 AF/yr. Also note the previously observed trend that the structural geology model results exhibit the lowest storage change with high pumping as compared to the other two models.

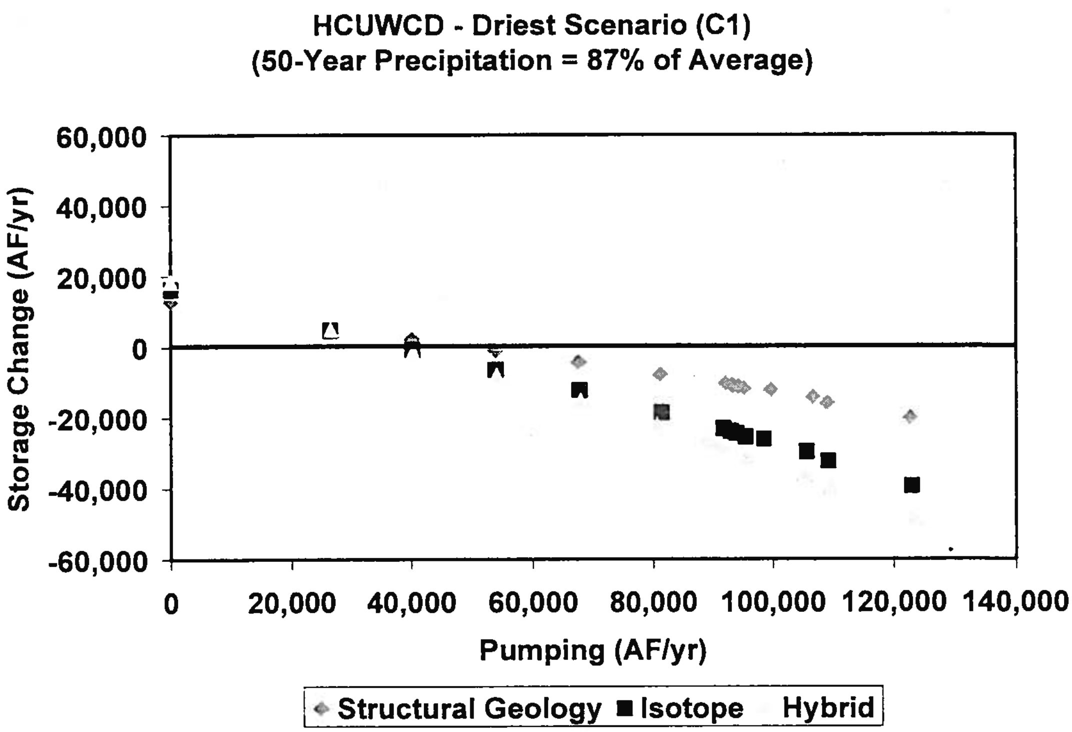


Figure 122. Simulation Results for the New HCUWCD Zone
Groundwater Pumping vs. Groundwater Storage Change within HCUWCD
Climatic Scenario C1 – Driest Conditions

Figure 123 presents the simulations that included the wettest conditions, about 131% of average precipitation for the entire 50-year simulation. Note that under these climatic conditions, storage change is zero when pumping is about 68,000 AF/yr. Also note the previously observed trend that the structural geology model results exhibit the lowest storage change with high pumping as compared to the other two models.

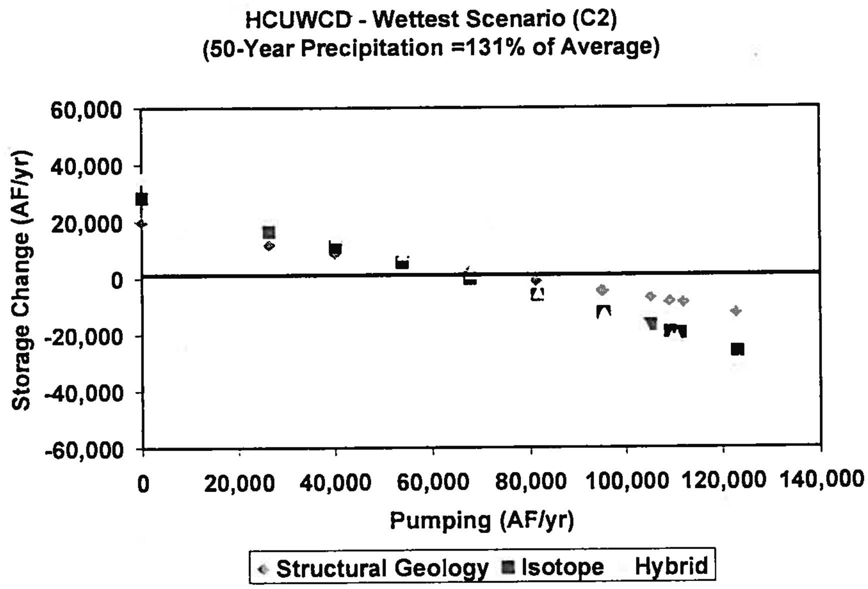


Figure 123. Simulation Results for the New HCUWCD Zone
Groundwater Pumping vs. Groundwater Storage Change within HCUWCD
Climatic Scenario C2 – Wettest Conditions

Figure 124 presents the simulations that included the lowest standard deviation climatic scenario, with an average precipitation of 94% for the entire 50-year simulation. Note that under these climatic conditions, storage change is zero when pumping is about 40,000 AF/yr.

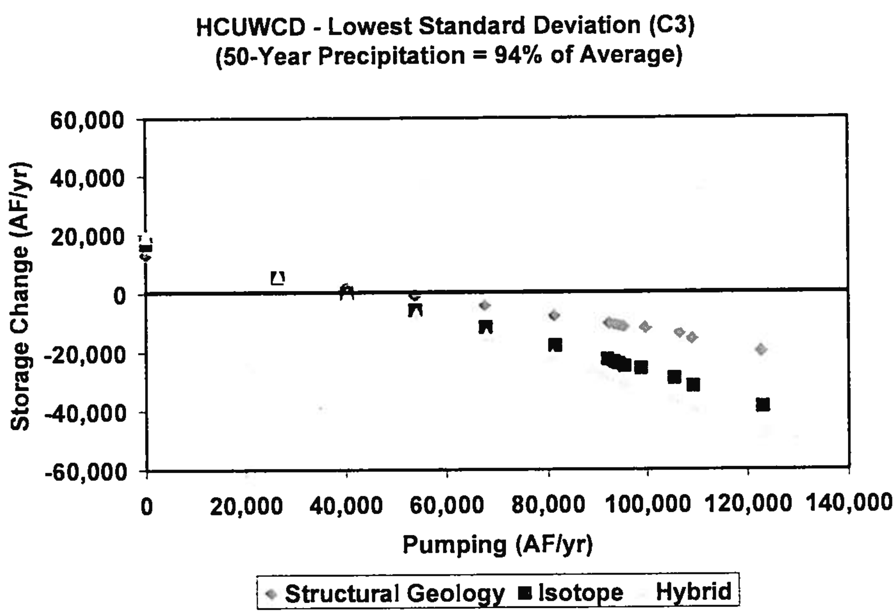


Figure 124. Simulation Results for the New HCUWCD Zone
Groundwater Pumping vs. Groundwater Storage Change within HCUWCD
Climatic Scenario C3 – Lowest Standard Deviation

Figure 125 presents the simulations that included the highest standard deviation climatic scenario, with an average precipitation of 111% for the entire 50-year simulation. Note that under these climatic conditions, storage change is zero when pumping is about 68,000 AF/yr.

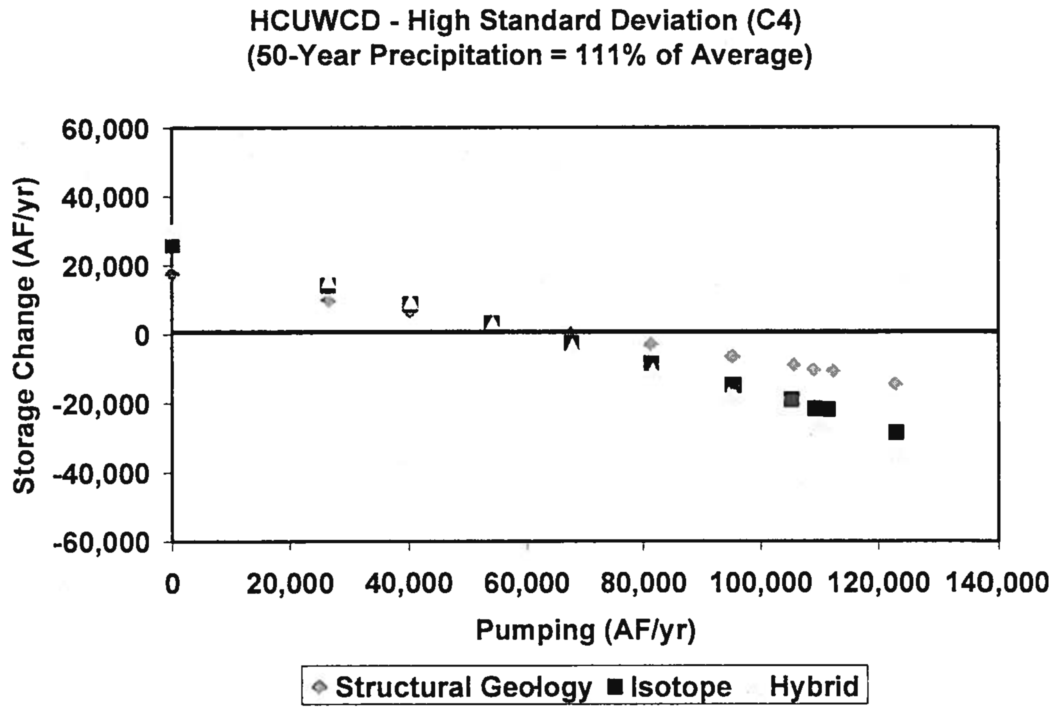


Figure 125. Simulation Results for the New HCUWCD Zone
Groundwater Pumping vs. Groundwater Storage Change within HCUWCD
Climatic Scenario C4 – Highest Standard Deviation

The final three climatic scenarios all represented average rainfall over the 50-year period. The three scenarios represented the range of standard deviations found in the Ni and others (2002) dataset: termed low, intermediate and high standard deviations. All three are presented in Figure 126. Figure 127 presents the low standard deviation scenarios, Figure 128 presents the intermediate standard deviation scenarios, and Figure 129 presents the high standard deviation scenarios. Note that, depending on the standard deviation, storage change is zero when pumping is between 40,000 AF/yr and 55,000 AF/yr.

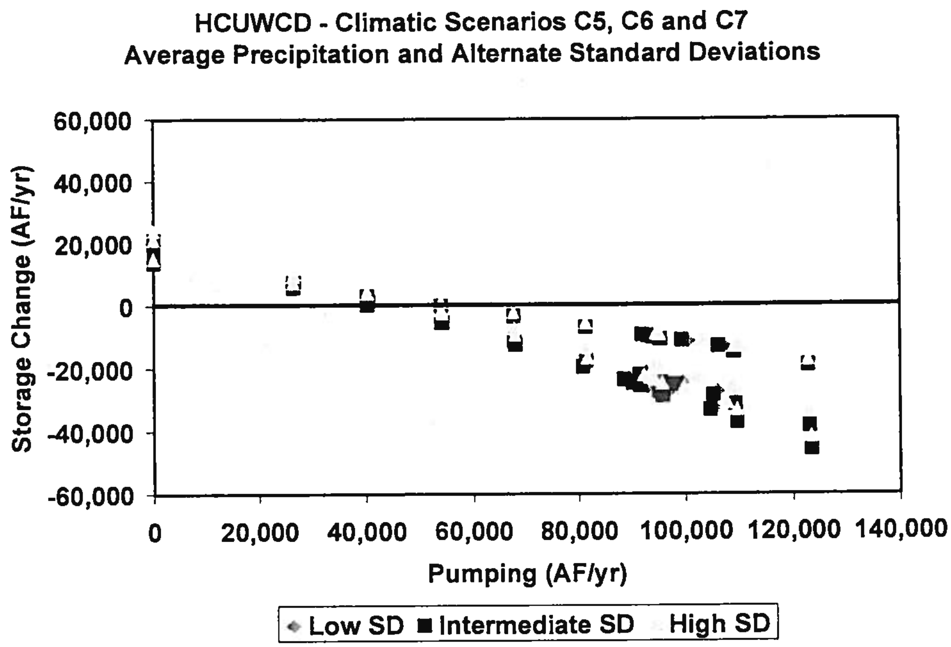


Figure 126. Simulation Results for the New HCUWCD Zone
Groundwater Pumping vs. Groundwater Storage Change within HCUWCD
Climatic Scenarios C5, C6, and C7 – Average Precipitation and Alternate Standard Deviations

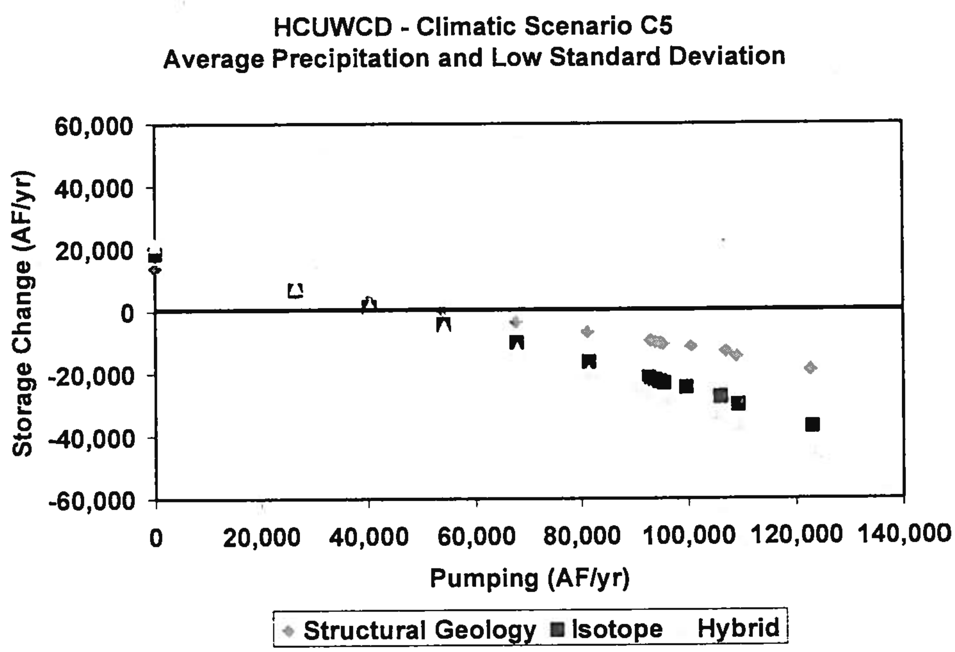


Figure 127. Simulation Results for the New HCUWCD Zone
Groundwater Pumping vs. Groundwater Storage Change within HCUWCD
Climatic Scenario C5 – Average Precipitation and Low Standard Deviation

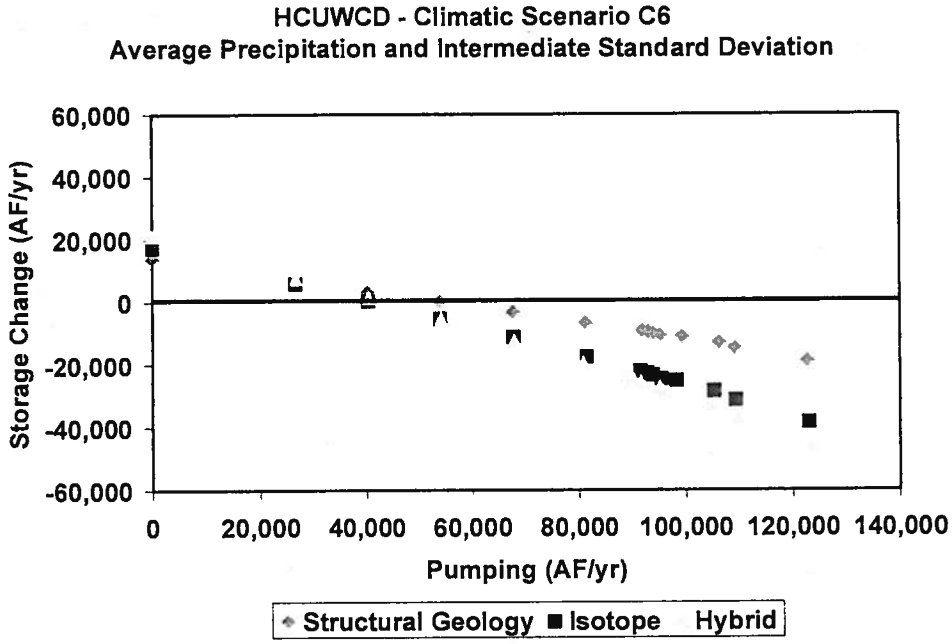


Figure 128. Simulation Results for the New HCUWCD Zone
Groundwater Pumping vs. Groundwater Storage Change within HCUWCD
Climatic Scenario C6 – Average Precipitation and Intermediate Standard Deviation

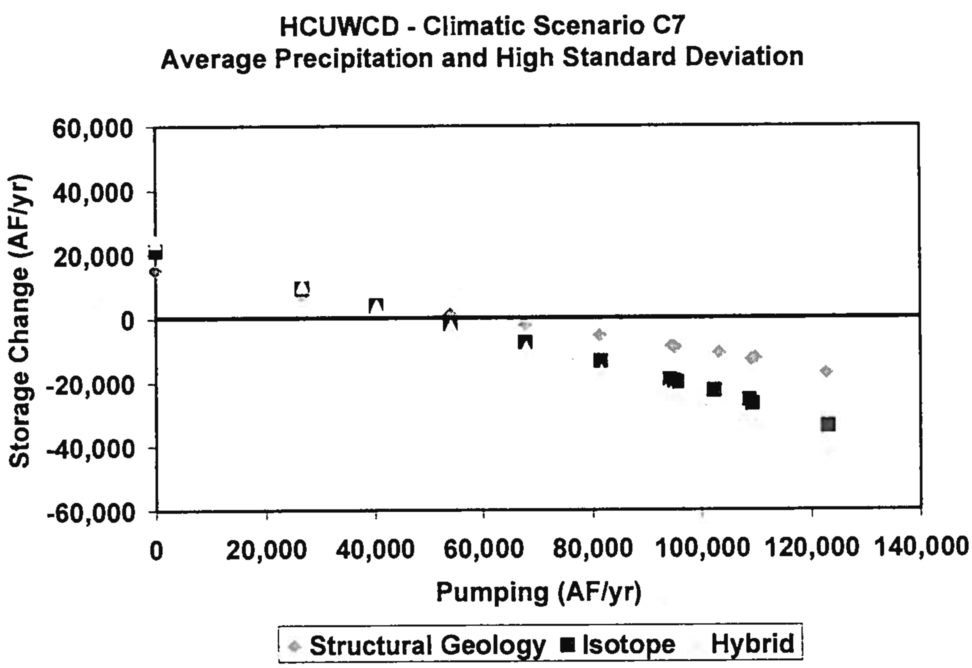


Figure 129. Simulation Results for the New HCUWCD Zone
Groundwater Pumping vs. Groundwater Storage Change within HCUWCD
Climatic Scenario C7 – Average Precipitation and High Standard Deviation

Based on the summaries of groundwater pumping vs. groundwater storage change within the new boundaries of the HCUWCD, zero storage change would be achieved with net pumping between 40,000 AF/yr and 68,000 AF/yr. Table 52 summarizes the results.

Table 52. Summary of Net Groundwater Pumping that Would Result in Zero Storage Change (50-Year Average)

Scenario Number	Climatic Scenario Description	Precipitation (% of Average)	Pumping (AF/yr)
C1	Driest	87	40,000
C2	Wettest	131	68,000
C3	Lowest Standard Deviation	94	40,000
C4	Highest Standard Deviation	111	68,000
C5	Average - Low Standard Deviation	100	40,000
C6	Average - Intermediate Standard Deviation	100	40,000
C7	Average - High Standard Deviation	100	54,000

If "sustainability" means maintaining a zero groundwater storage change, HCUWCD would need to reduce pumping from what has historically occurred, and what is currently permitted under the HCUWCD rules based on the results of this investigation. However, in order to put the issue of zero storage change into some perspective, several hydrographs of wells were constructed to investigate groundwater storage changes over time in these locations for selected simulations. The locations of the selected wells are shown in Figure 130.

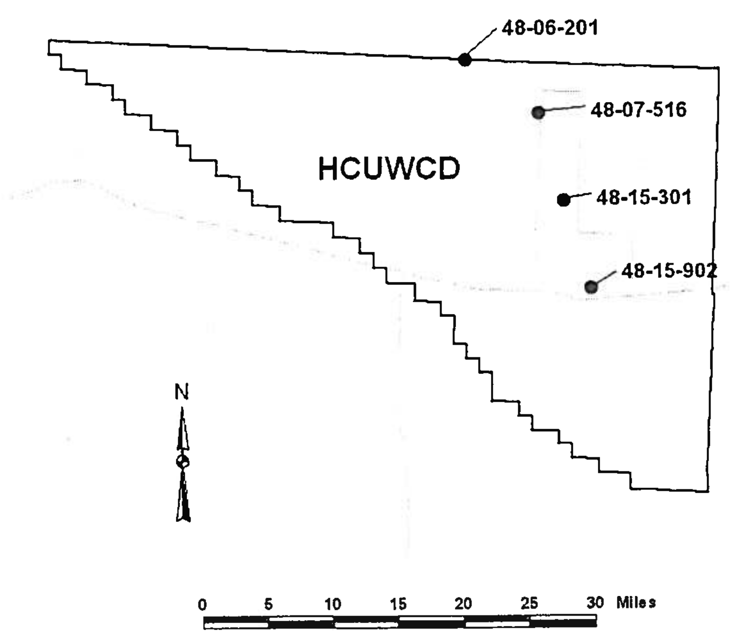


Figure 130. Location of Selected Wells Used for Hydrograph Analysis

Table 53 summarizes the simulations that were used in the analysis. Note that simulations that resulted in between 0 and -10,000 AF/yr of storage change were used. Also note that a variety of climatic scenarios were used, as well as a sampling of all three models (structural geology, isotope geochemistry and hybrid). The figure numbers for the hydrographs are also shown in Table 53.

Table 53. Summary of Simulations Used in Hydrograph Analysis

Simulation Number	Figure Number	Model	Climatic Scenario	Pumping (AF/yr)	Groundwater Storage Change (AF/yr)
260	131	M2 (Isotope Geochemistry)	C3 (Low SD)	40,000	0
255	132	M3 (Hybrid)	C1 (Driest)	40,000	-1,000
320	133	M2 (Isotope Geochemistry)	C2 (Wettest)	81,000	-6,000
316	134	M1 (Structural Geology)	C1 (Driest)	81,000	-8,000
139	135	M1 (Structural Geology)	C5 (Avg Precip, Low SD)	94,000	-10,000

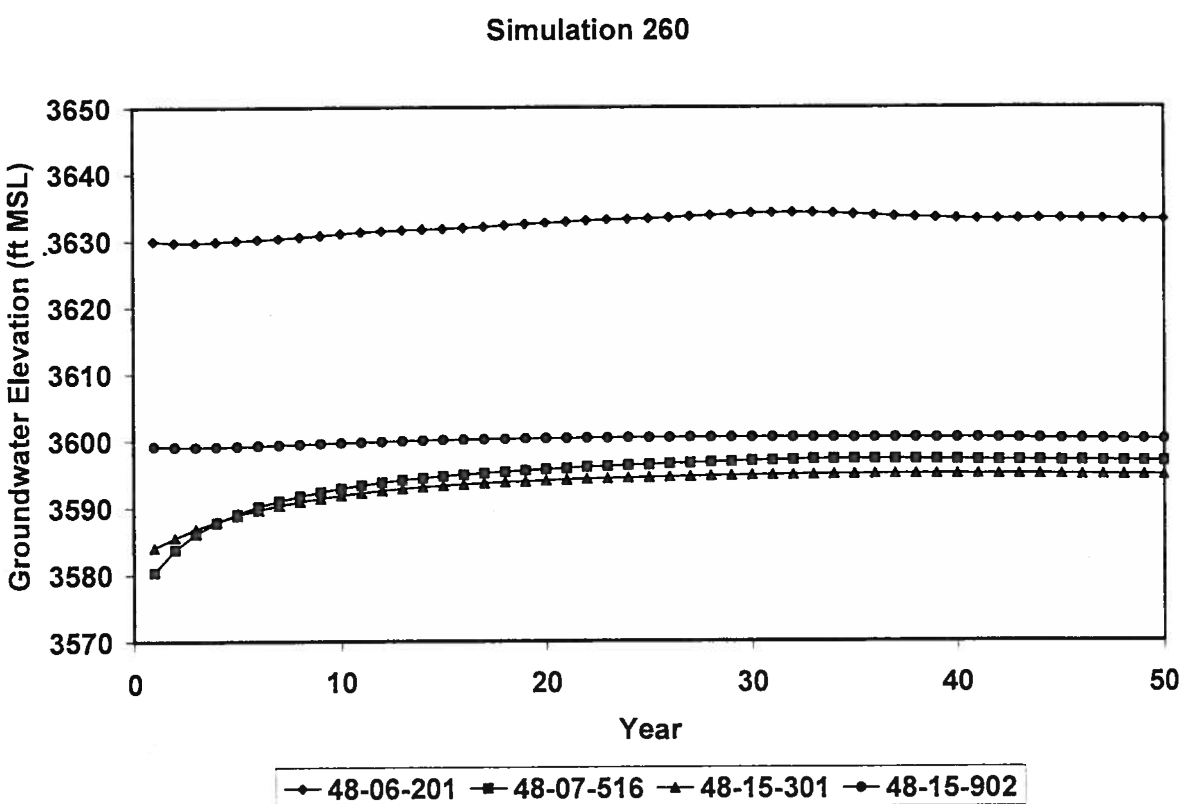


Figure 131. Hydrographs for Simulation 260

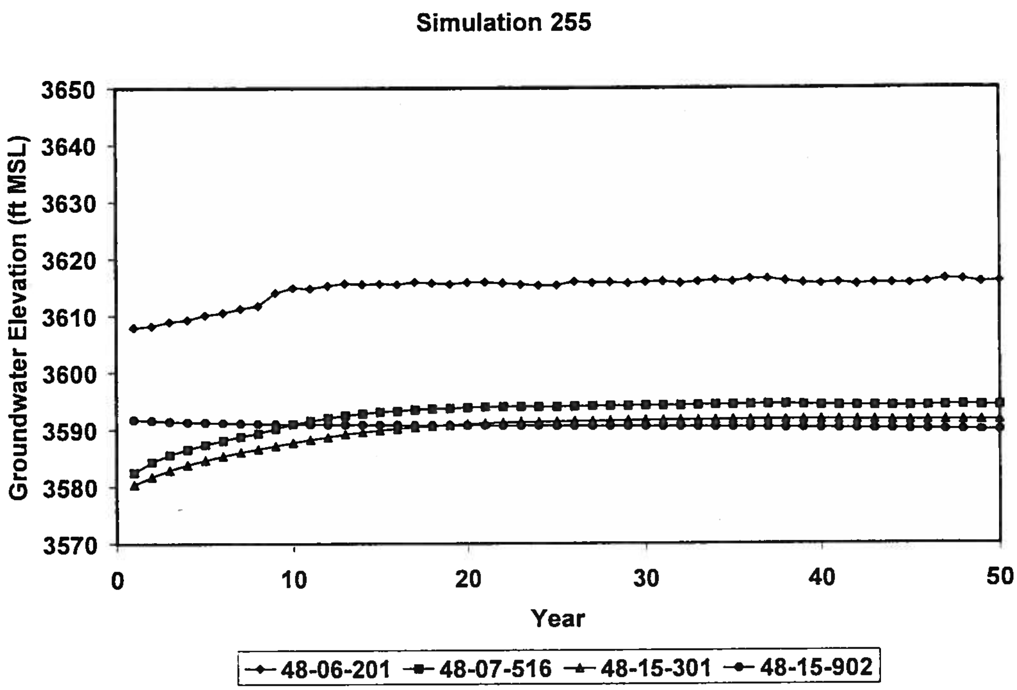


Figure 132. Hydrographs for Simulation 255

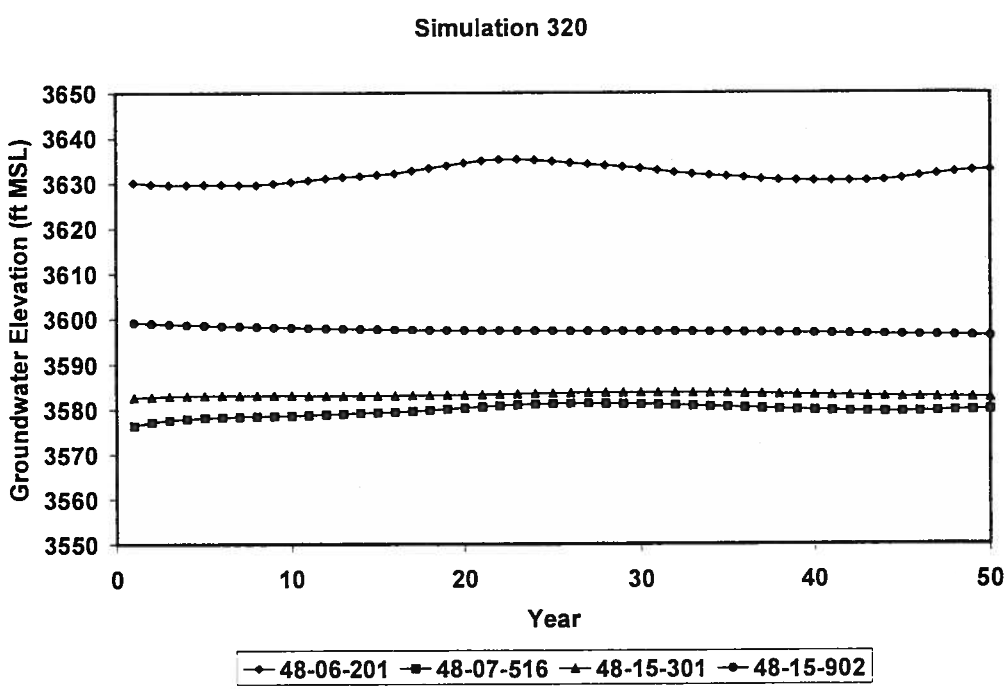


Figure 133. Hydrographs for Simulation 320

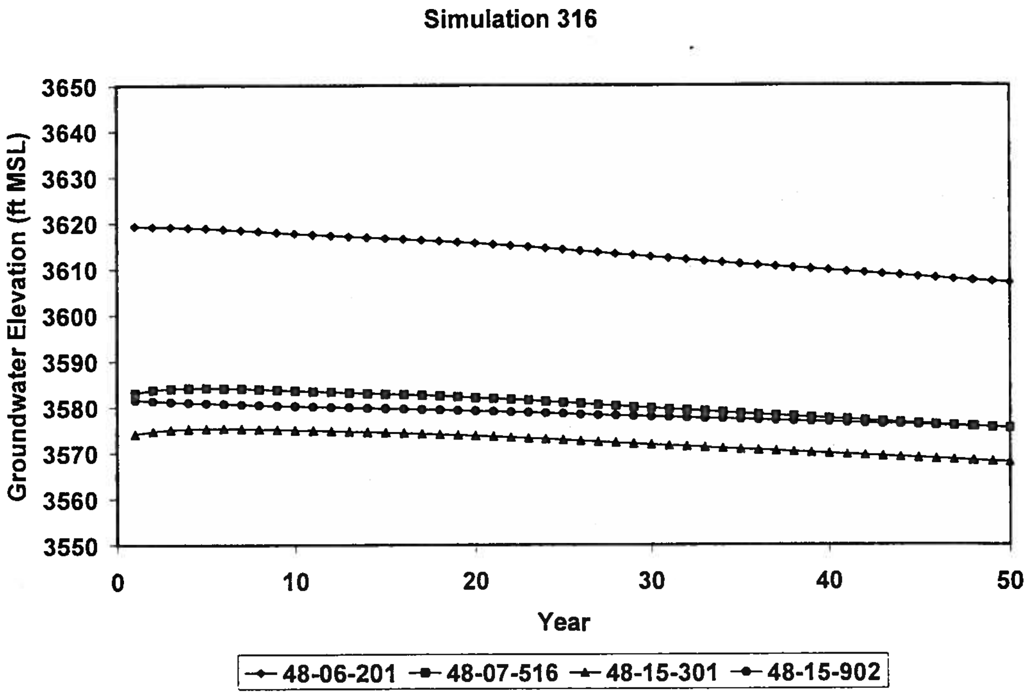


Figure 134. Hydrographs for Simulation 316

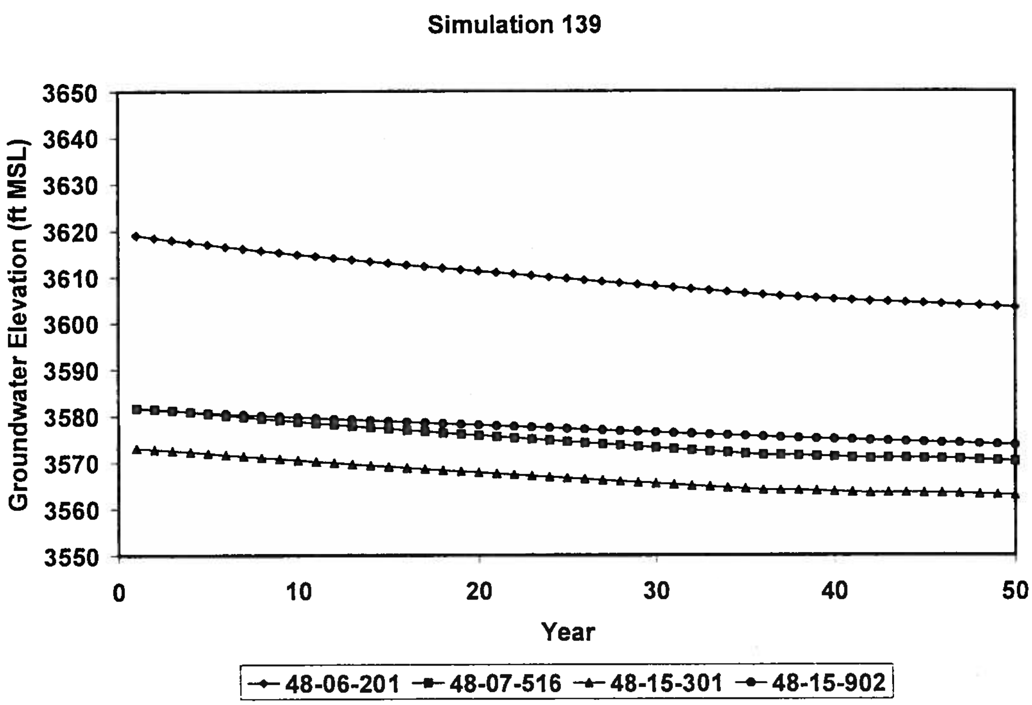


Figure 135. Hydrographs for Simulation 139

Simulations 260 and 255 represent a zero or near zero storage change condition throughout the HCUWCD. However, three of the hydrographs of the wells demonstrate an observable increase in groundwater elevation during the 50-year simulation. Simulation 320 represents a simulation that resulted in about a 6,000 AF/yr storage decline, yet the hydrographs of these four wells appear to be qualitatively unchanged over the 50-year simulation. Simulations 316 and 139 represent storage declines of between 8,000 and 10,000 AF/yr, and the hydrographs clearly indicate a decline in groundwater elevation of about 5 feet over 50 years to slightly over 10 feet over 50 years.

This analysis of linking groundwater storage decline to groundwater elevation changes can be advanced by presenting the average drawdown after 50 years over the entire HCUWCD area, and over the irrigated area of HCUWCD (shown in Figure 136).

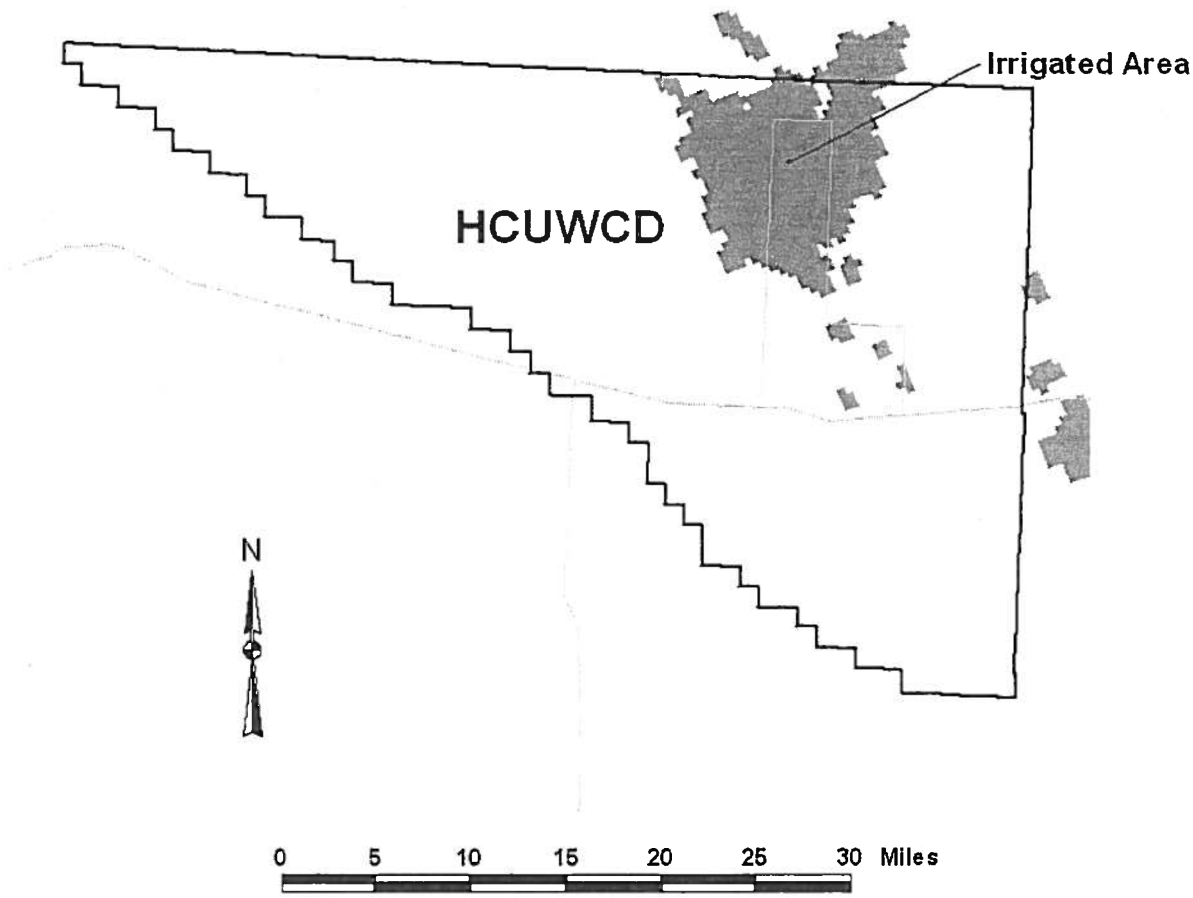


Figure 136. Irrigated Area of HCUWCD

Figure 137 presents groundwater pumping vs. total drawdown after 50 years (averaged over the entire area within the new boundaries of HCUWCD) for all simulation. Note that drawdown is positive when groundwater levels at the end of the 50-year simulation are lower than at the beginning of the simulation. Therefore, when pumping is about 81,000 AF/yr, drawdown is between 2 and 9 feet, depending on the model used and the climatic scenario. This scenario is representative of the 2001 pumping conditions. When pumping is about 95,000 AF/yr, drawdown ranges between 5 feet and 13 feet. This is representative of the current validation permit limits.

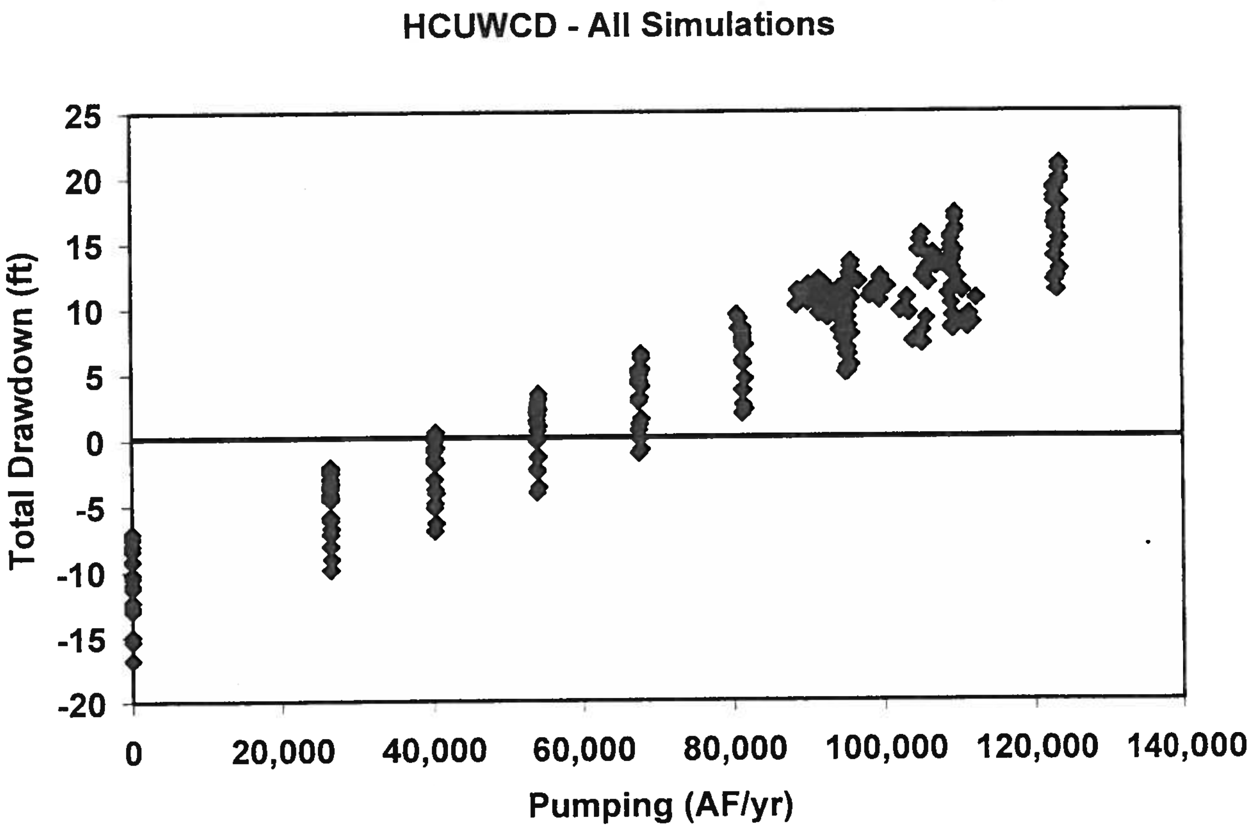


Figure 137. Summary of Drawdown Estimates after 50 Years within HCUWCD for all Simulations

Figure 138 presents groundwater pumping vs. total drawdown after 50 years (averaged over the irrigated area within the new boundaries of HCUWCD) for all simulation. Note that drawdown is positive when groundwater levels at the end of the 50-year simulation are lower than at the beginning of the simulation. Therefore, when pumping is about 81,000 AF/yr, drawdown is between -3 feet (rise of 3 feet) and 10 feet, depending on the model used and the climatic scenario. This scenario is representative of the 2001 pumping conditions. When pumping is about 95,000 AF/yr, drawdown ranges between 5 feet and 21 feet. This is representative of the current validation permit limits.

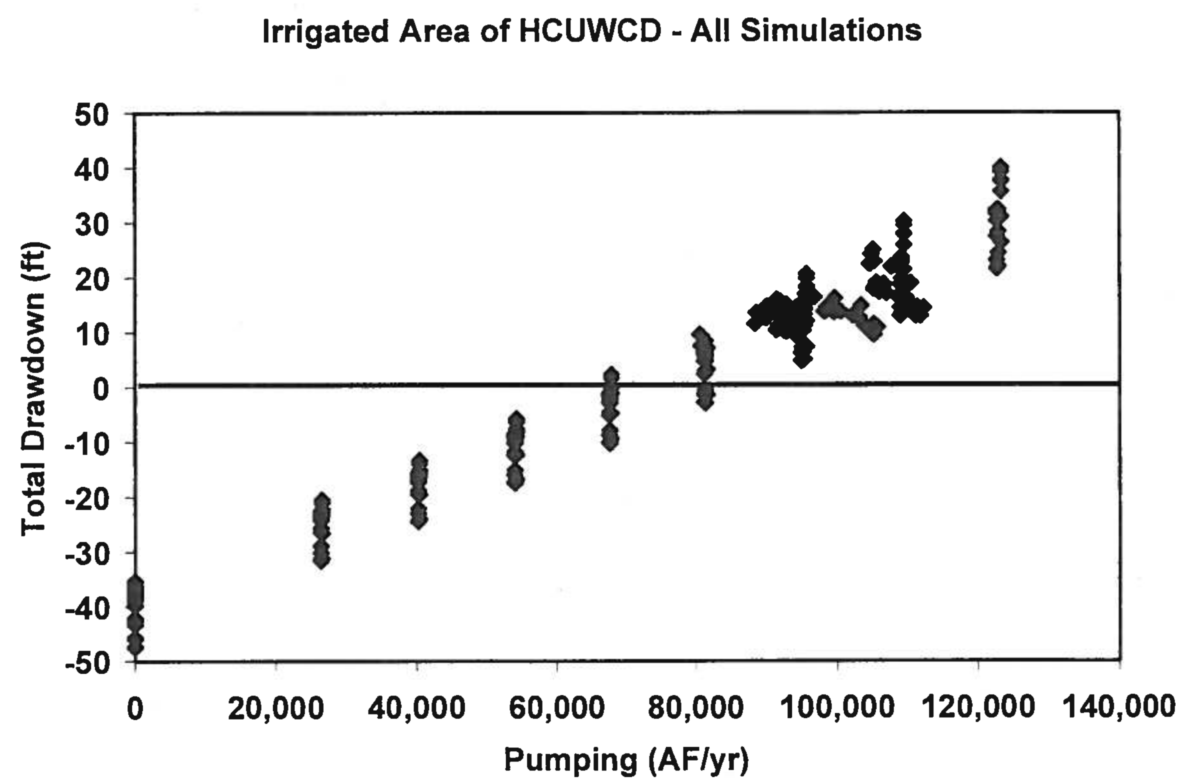


Figure 138. Summary of Drawdown Estimates after 50 Years within Irrigated Area of HCUWCD for all Simulations

The relationship between groundwater storage change within HCUWCD and average drawdown after 50 years for all simulations is presented in Figures 139 and 140. Figure 139 plots groundwater storage change in HCUWCD and Average Drawdown for all of HCUWCD for all simulations, with each model shown separately.

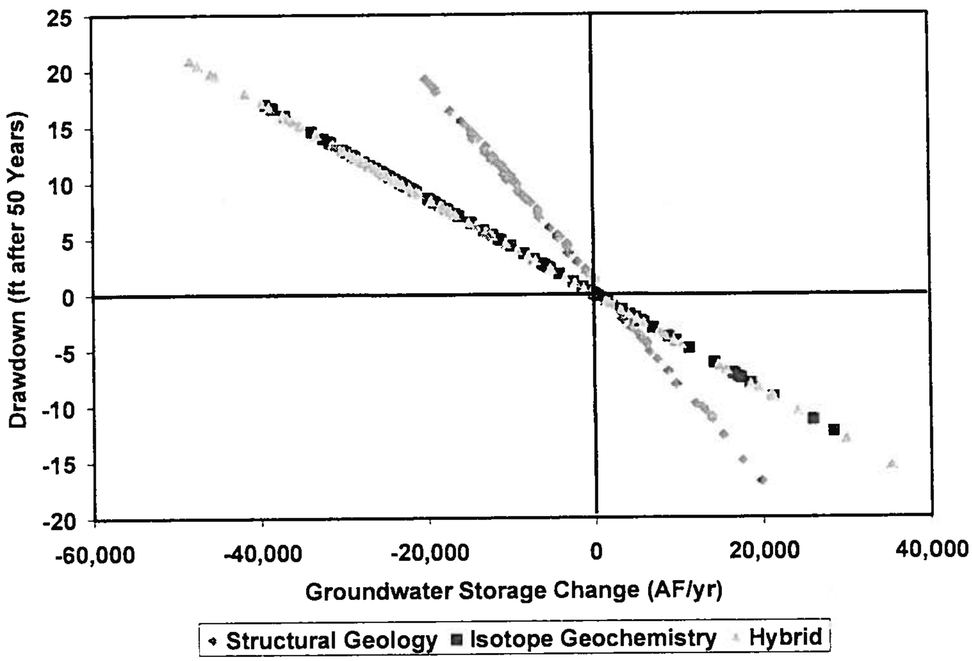


Figure 139. Groundwater Storage Change in HCUWCD vs. Average Drawdown after 50 Years in HCUWCD

Note that for zero storage change, drawdown is also zero for all three models. For equal storage declines, the structural geology model suggests that the drawdown will be greater than for the other two models. This is due to different specific storages and, hence, different storativities between the models. The structural geology model assumes that the specific storage in the HCUWCD area is 1.1E-04 ft^{-1}. The isotope geochemistry model and the hybrid model assume a value of 2.0E-04 ft^{-1}. Assuming an aquifer thickness of 1,000 ft, this translates to storativity values of 0.11 and 0.2, respectively. Since the isotope geochemistry model and the hybrid model have a storativity value nearly twice that of the structural geology model, the relationship in Figure 139 between the three models is expected, and highlights the sensitivity of that parameter.

In order to understand what the groundwater storage change rate throughout HCUWCD means in terms of drawdown within the irrigated area, Figure 140 plots groundwater storage change in HCUWCD vs. the drawdown in the irrigated area of HCUWCD.

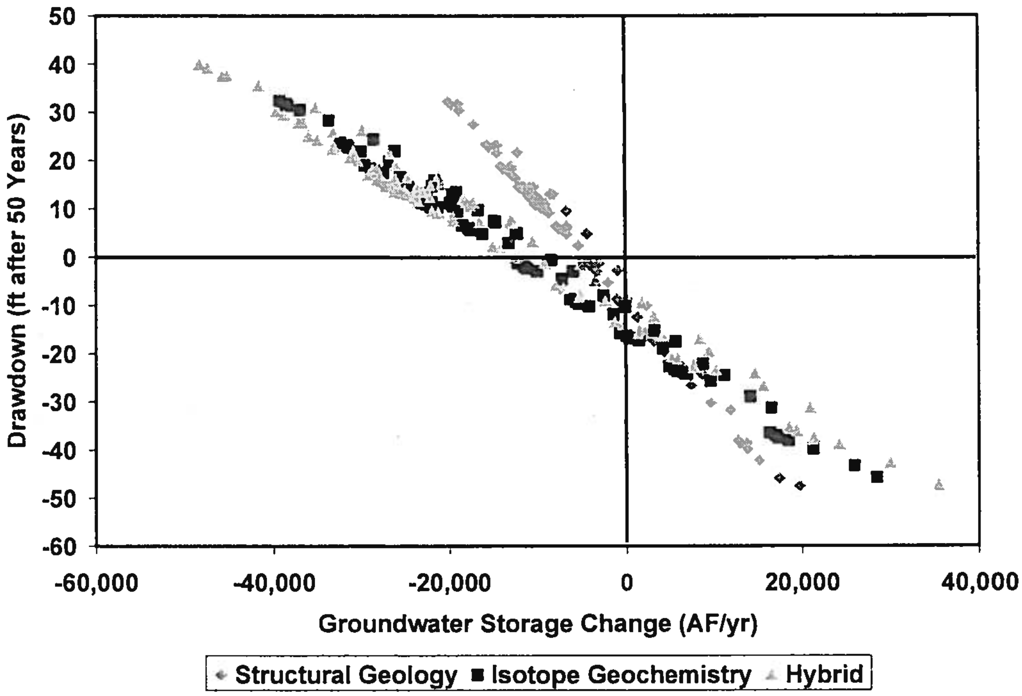


Figure 140. Groundwater Storage Change in HCUWCD vs.
Average Drawdown after 50 Years in Irrigated Area of HCUWCD

Note that at zero storage change, a rise in groundwater elevations of between 9 and 17 feet is estimated depending on the model and the climatic scenario after 50 years in the irrigated area. Zero drawdown in the irrigated area occurs when the groundwater storage decline in the entire HCUWCD is between about 3,000 AF/yr and about 14,000 AF/yr. Based on the plot of pumping vs. groundwater storage change (previously shown as Figure 87), pumping at 67,000 AF/yr would always result in a storage decline of less than 14,000 AF/yr. Pumping between 67,000 and 95,000 AF/yr would result in less than 14,000 AF/yr of groundwater storage decline in wet, average, and slightly below average precipitation periods.

9.0 SUMMARY AND CONCLUSIONS

The Dell City area may become a source of municipal water supply for El Paso. In order to better understand the area and develop estimates of groundwater yields from the area, this study was completed by El Paso Water Utilities for internal analysis. The study included a review of previous work, the development of three numerical groundwater flow models to test various aspects of the conceptual model of groundwater flow in the area, and the application of the three groundwater flow models under various climatic and pumping scenarios to estimate groundwater yields in the area. This report and the model files have been forwarded to the Texas Water Development Board for their future use. As such, this report and the associated models are not official TWDB Groundwater Availability Models (GAMs). However, it is hoped that this effort will assist the TWDB in their development of GAMs for the area.

Significant conclusions of this study are:

- Total inflow (recharge plus boundary flows) estimates for the entire model domain under predevelopment conditions ranged between 79,000 and 104,000 AF/yr, depending on the model used
- Average total inflow (recharge plus boundary flows) estimates from 1948 to 2002 ranged between 87,000 and 114,000 AF/yr, depending on the model used. Note that total inflow increased as a result of a combination of pumping and high recharge in latter years of the simulation period.
- The recharge estimates are generally consistent with and slightly higher than previous estimates as documented in the literature.
- Evapotranspiration from the playa area east of Dell City prior to 1948 ranged from 79,000 to 104,000, depending on the model used to make the estimate.
- Average evapotranspiration from the playa from 1948 to 2002 ranged from 49,000 to 67,000 AF/yr.
- Average total consumptive pumping in the area from 1948 to 2002 was about 88,000 AF/yr
- Irrigated acreage in the area rose from less than 10,000 acres in 1948 to about 25,000 acres in the mid 1950s. From the mid 1950s to the mid 1980s, irrigated acreage fluctuated between about 20,000 acres to as high as 45,000 acres. From the early 1980s to 2002, irrigated acreage was relatively constant at slightly over 20,000 acres, except for declines in 1993 and 1994.
- Prior to 1993 and the widespread use of center pivot irrigation, consumptive duty on irrigated lands was about 3 AF/ac. After 1993, consumptive duty on irrigated lands was about 5 AF/ac. Due to the nature of the modeling approach used, it is not possible to make any estimates or draw any conclusions regarding total pumping (consumptive pumping plus leaching fraction), or estimate the leaching fraction.
- Historic groundwater pumping from 1948 to 2002 in the new boundary of HCUWCD averaged about 80,000 AF/yr. This pumping resulted in:
    - Between 3,000 and 19,000 AF/yr of increased inflow from New Mexico (depending on the model used).
    - Between 2,000 and 9.000 AF/yr of increased inflow from the Diablo Plateau, southwest of HCUWCD (depending on the model used).
    - Between 0 and 1,000 AF/yr of increased inflow from the area in Hudspeth County east of HCUWCD (depending on the model used).

- Between 25,000 and 37,000 AF/yr of decreased evapotranspiration for the playa area within HCUWCD (depending on the model used).
- Between 21,000 and 39,000 AF/yr of decreased groundwater storage within HCUWCD (depending on the model used).

- Groundwater yield in the Dell City area ranges from 54,000 to 95,000 AF/yr (net or consumptive pumping), depending on climatic condition, and depending on the definition of "sustainability" that could be applied by the board of HCUWCD.

10.0 REFERENCES

Alley, William M., Reilly, Thomas E., and Franke, O. Lehn, 1999. Sustainability of Groundwater Resources. U.S. Geological Survey Circular 1186.

Ashworth, John B., 1995. Groundwater Resources of the Bone Spring-Victorio Peak Aquifer in the Dell Valley Area, Texas. Texas Water Development Board Report 344.

Bjorklund, L.J., 1957. Reconnaissance of Groundwater Conditions in the Crow Flats Area, Otero County, New Mexico. State of New Mexico, State Engineer Office, Technical Report No. 8.

Blair, A.W., 2002a. Consumptive Irrigation Requirements for 2001. Memorandum to Glen Gilmore, Hudspeth Underground Water Conservation District No. 1, Dell City Texas.

Blair, A.W., 2000b. Engineer's Report. Presentation to Hudspeth County Underground Water Conservation District No. 1, March 19, 2002 Board of Directors Meeting, Dell City, Texas.

Boyd, F. M., and Kreitler, C. W., 1986, Hydrogeology of a gypsum playa, northern Salt Basin, Texas: El Paso Geological Society, Guidebook 18, p. 170-183.

Bredehoeft, John D., 2002. The water budget myth revisited: Why hydrogeologists model. Groundwater. Vol. 40 No. 4 pp. 340-345.

Brown and Caldwell, 2001. Dell Valley Water Resources Evaluation. Prepared for Hunt Building Corporation.

DeJong, H.W. and Addy, S.K., 1992a. Only relatively small production seen in basins of far West Texas. Oil & Gas Journal, January 20, 1992.

DeJong, H.W. and Addy, S.K., 1992b. Broad view indicated hydrocarbon potential low in far West Texas. Oil & Gas Journal, January 27, 1992.

Dietrich, J.W., Owen, D.E., Shelby, C.A. and Barnes, V.E., 1995. Geologic Atlas of Texas, Van Horn-El Paso Sheet. University of Texas at Austin, Bureau of Economic Geology. 1:250,000 Scale.

Doherty, John, 2004. PEST: Model Independent Parameter Estimation, User's Manual, 5th Edition. Watermark Numerical Computing.

Eastoe, C.J, and Hibbs, B.J., 2005. Stable and Radiogenic Isotope Evidence Relating to Regional Groundwater Flow Systems Originating in the High Sacramento Mountains, New Mexico. American Geophysical Union Fall Meeting, San Francisco, California, Session H33G, p.297

Far West Texas Regional Planning Group, 2001. Far West Texas Regional Water Plan. Prepared for Texas Water Development Board. Prepared by LBG-Guyton Associates, Freese and Nichols, Inc., MCi Consulting Engineers, M3H Consulting, Inc., the Rio Grande Council of Governments, and members of the Far West Texas Regional Water Planning Group.

Far West Texas Regional Planning Group, 2006. Far West Texas Water Plan. Prepared for Texas Water Development Board.

Finch Jr., Steven T. (2002). Hydrogeologic Framework of the Salt Basin and Development of Three-Dimensional Ground-Water Flow Model. Prepared for New Mexico Interstate Stream Commission by John Shomaker & Associates, Inc., Albuquerque, New Mexico.

Finch, Steven T. and Bennett, Jeffrey B., 2002. Hydrogeologic Evaluation of the Northern part of Culberson County Groundwater Conservation District, Culberson County, Texas. Prepared for Culberson County Groundwater Conservation District, Van Horn, Texas by John Shomaker & Associates, Inc., Albuquerque, New Mexico.

Freeze, R. Allan, and Cherry, John A., 1979. Groundwater. Prentice Hall. Englewood Cliffs, New Jersey.

Gates, Joseph S., White, Donald E., Stanley, W.D. and Ackerman, Hans D., 1980. Availability of Fresh and Slightly Saline Groundwater in the Basins of Westernmost Texas. Texas Department of Water Resources Report 256.

George, Peter, Mace, Robert E., and Mullican, William F., 2005. The Hydrogeology of Hudspeth County, Texas. Texas Water Development Board Report 364.

Goetz, L. K., 1977. Quaternary faulting in Salt Basin grabens, West Texas: unpublished M.A. thesis, The University of Texas at Austin, 136 p.

Gooch, Thomas C., Salazar, A. Andres, Kiel, Simone, and Ashworth, John, 2006. Integrated Water Management Strategies for the City and County of El Paso. Prepared for Far West Texas Water Planning Group.

Groeneveld, David P. and Baugh, William M., 2002. Mapping and Estimating Evapotranspiration For Dell Valley, Texas. Report Prepared for El Paso Water Utilities, El Paso, Texas. December 9, 2002. HydroBio Advanced Remote Sensing, Santa Fe, New Mexico.

Harbaugh, Arden W., 1990. A Computer Program for Calculating Subregional Water Budgets Using Results from the U.S. Geological Survey Modular Three-dimensional Finite-difference Ground-water Flow Model. U.S. Geological Survey Open-File Report 90-392.

Harbaugh, Arden W., Banta, Edward R., Hill, Mary C., McDonald, Michael G., 2000. MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model —User Guide to Modularization Concepts and the Ground-Water Flow Process. U.S. Geological Survey Open File Report 00-92, Reston Virginia.

Hibbs, Barry J., Boghici, Radu N., Hayes, Mark E., Ashworth, John B., Hanson, Adrian T., Samani, Zohrab A., Kennedy, John F., and Creel, Bobby J., 1997. Transboundary Aquifers of the El Paso/Ciudad Juarez/Las Cruces Region. Report Prepared by Texas Water Development Board and New Mexico Water Resources Research Institute for US Environmental Protection Agency

Hill, Mary C. and Tiedeman, Claire R., 2007. Effective Groundwater Model Calibration with Analysis of Data, Sensitivities, Predictions, and Uncertainties. Wiley-Interscience, Hoboken, New Jersey.

Huntoon, Peter W., 1995. Is It Appropriate to Apply Porous Media Groundwater Circulation Models to Karstic Aquifer. In: El-Kadi, Aly I., Groundwater Models for Resources Analysis and Management. Lewis Publishers, Boca Raton, pp 339-358.

Huff, G.F. and Chace, D.A., 2006. Knowledge and Understanding of the Hydrogeology of the Salt Basin in South-central New Mexico and Future Study Needs. U.S. Geological Survey Open File Report 2006-1358. Reston, Virginia.

Hydrosphere Data Products, Inc., 1992. Monthly climatic data summaries. North America (CD-ROM).

King, Philip B., 1965. Geology of the Sierra Diablo Region, Texas. U.S. Geological Survey Professional Paper 480.

Kreitler, Charles W., Mullican, William F., and Nativ, Ronit, 1990. Hydrogeology of the Diablo Plateau, Trans-Pecos Texas. In: Hydrogeology of Trans-Pecos Texas. The University of Texas at Austin, Bureau of Economic Geology Guidebook 25.

Kreitler, C.W., Raney, J.A., Nativ, R., Collins, E.W., Mullican, W.F., Gustavson, T.C., and Henry, C.D., 1987. Siting a low-level radioactive waste disposal facility in Texas, volume four – geologic and hydrologic investigations of State of Texas and University of Texas lands: The University of Texas at Austin, Bureau of Economic Geology, report prepared for Texas Low-Level Radioactive Waste Disposal Authority under Interagency Contract No. IAC(86-87)1790.

Livingston Associates and John Shomaker & Associates, 2002. Tularosa Basin and Salt Basin Regional Water Plan, 2000-2040. Prepared for South Central Mountain RC&D Council, Inc., Carrizozo, NM.

Long, J.C.S., Remer, J.S. Wilson, C.R., and Witherspoon, P.A., 1982. Porous media equivalents for networks of discontinuous fractures. Water Resources Research, v18. pp 645-658.

Mace, Robert E., 2001, Estimating transmissivity using specific-capacity data: Bureau of Economic Geology, The University of Texas at Austin, Geological Circular 01-2, 44 p.

Maxey, G.B. and Eakin, T.E., 1949. Groundwater in White River Valley, White, Pine, Nye and Lincoln Counties, Nevada. Nevada State Engineer's Office Water Resources Bulletin, v28, no 3, pp 141-158.

Mayer, James Roger, 1995. The Role of Fractured in Regional Groundwater Flow: Field Evidence and Model Results from the Basin-and-Range of Texas and New Mexico. Ph.D. Dissertation, University of Texas.

Meinzer, O.E., 1932. Outline of Methods for Estimating Ground-water Supplies. U.S. Geological Survey Water-Supply Paper 638-C.

Mullican, William F. and Mace, Robert E., 2001. The Diablo Plateau Aquifer. Chapter 18 of Aquifers of West Texas. Texas Water Development Board Report 356.

Ni, Fenbiao; Cavazos, Tereza; Hughes, Malcolm K., Comrie, Andrew C., and Funkhouser, Gary (2002). Cool-season precipitation in the southwestern USA since AD 1000: comparison of linear and nonlinear techniques for reconstruction. International Journal of Climatology, Vol. 22, Issue 13, pp. 1645-1662.

Nielson, P.D. and Sharp, J.M., 1985. Tectonic controls on the hydrogeology of the Salt Basin, Trans-Pecos Texas: in Dickerson, P.W. and Muehlberger, W.R. (eds.), Structure and Tectonics of Trans-Pecos Texas: West Texas Geological society Field Conf. 85-81.

O'Neill, J. Michael and Nutt, Constance J., 1998. Geologic Map of the Cornudas Mountains. U.S. Geological Survey Geologic Investigation Series I-2631.

Parizek, Richard R., 1979. Recommended Locations for Flood-Water Recharge Wells for Cornudas, North and Culp Draws and for Hitson, C and L and Washburn Draws, Hudspeth County, Texas. Report to U.S. Department of Agriculture Soil Conservation Service.

Quinlan, J.F., Davis, G.J., and Worthington, S.R.H, 1992. Rationale for the design of cost-effective monitoring systems in limestone and dolomite terrains, Proc. 8th Waste Testing and Quality Assurances Symposium, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, and Office of Research and Development, Washington D.C.

Reed, Ed L., 1965. A Study of Groundwater Reserves, Capitan Reef Reservoir, Hudspeth and Culberson Counties, Texas. Report prepared for Diablo Farms, Dallas, Texas.

Reed, Ed L., 1973. A Review of the Groundwater Potential, Diablo Farms Area, Culberson County, Texas. Report prepared for Amarex, Inc, Oklahoma City, Oklahoma.

Reed, Ed L., 1980. An Update of the Groundwater Potential, Diablo Farms Area, Culberson County, Texas. Report prepared for Amarex, Inc., Oklahoma City, Oklahoma.

Rumbaugh, James O., 2004. Guide to Using Groundwater Vistas. Environmental Simulations, Inc., Reinholds, Pennsylvania.

Sauter, M., 1993. Double Porosity models in karstified limestone aquifers, field validations and data provision, Hydrologic Processes in Karst Terrains, International Association of Hydrologic Sciences Publication 207.

Scalapino, Ralph A., 1950. Development of Groundwater for Irrigation in the Dell City Area, Hudspeth County. Texas. Texas Board of Water Engineers Bulletin 5004.

Sharp, John M., 1989. Regional Groundwater Systems in Northern Trans-Pecos Texas. In: Structure and Stratigraphy of Trans-Pecos Texas. American Geophysical Union Field Trip Guidebook T317.

Sharp, John M., 2001. Regional Groundwater Flow Systems in Trans-Pecos Texas. Chapter 4 of Aquifers of West Texas. Texas Water Development Board Report 356.

Stone, Dan B., Moomaw, Cynthia, L, and Davis, Andy, 2001. Estimating recharge distribution by incorporating runoff from mountainous areas in an alluvial basin in the Great Basin region of the southwestern United States. Groundwater, v39, no 6, pp 807-818.

Tolman. C.F., 1937. Ground Water. McGraw-Hill, New York.

Uliana, Matthew M., 2001. The Geology and Hydrogeology of the Capitan Aquifer: A Brief Overview. Chapter 11 of Aquifer of West Texas. Texas Water Development Board Report 356.

Urbanczyk, Kevin, Rohr, David and White, John C., 2001. Geologic History of West Texas. Chapter 2 of Aquifers of West Texas. Texas Water Development Board Report 356.

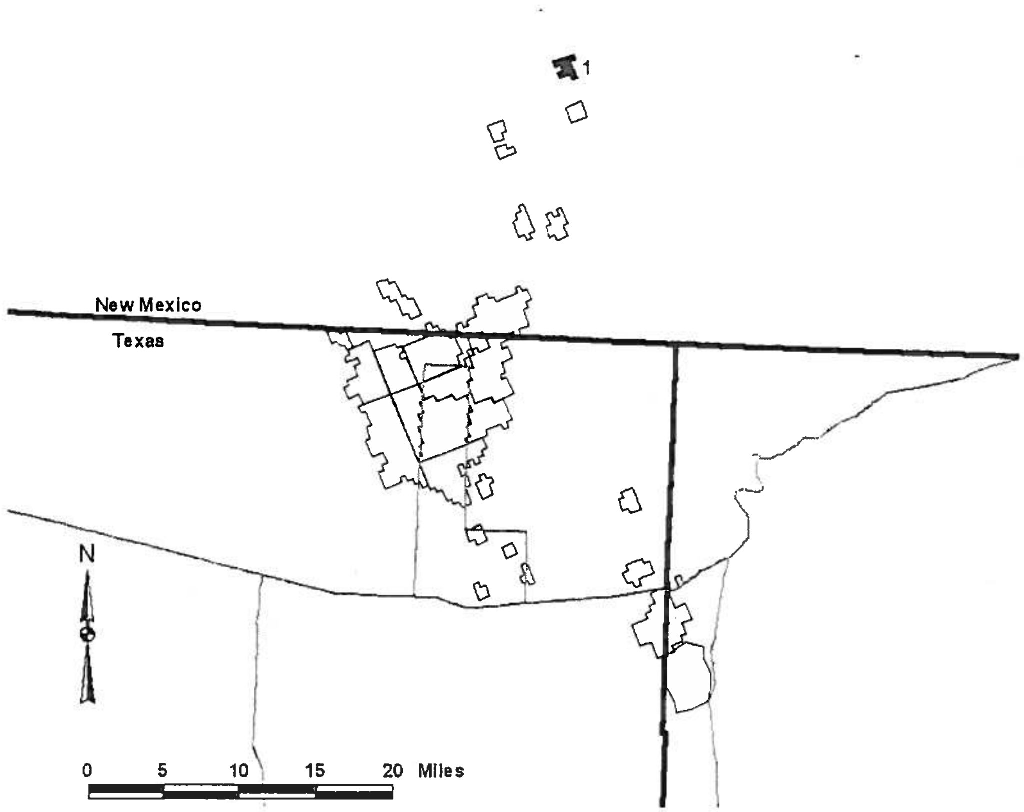
White. Donald E., Gates, Joseph S., Smith, James T. and Fry, Bonnie, J., 1980. Groundwater Data for the Salt Basin, Eagle Flat, Red Light Draw, Green River Valley, and Presidio Bolson in Westernmost Texas. Texas Department of Water Resources Report 259.

White, William B., 1999. Groundwater Flow in Karstic Aquifers. In: Delleur, Jacques W., The Handbook of Groundwater Engineering. CRC Press, Boca Raton, FL. Pp 18-1 to 18-36.

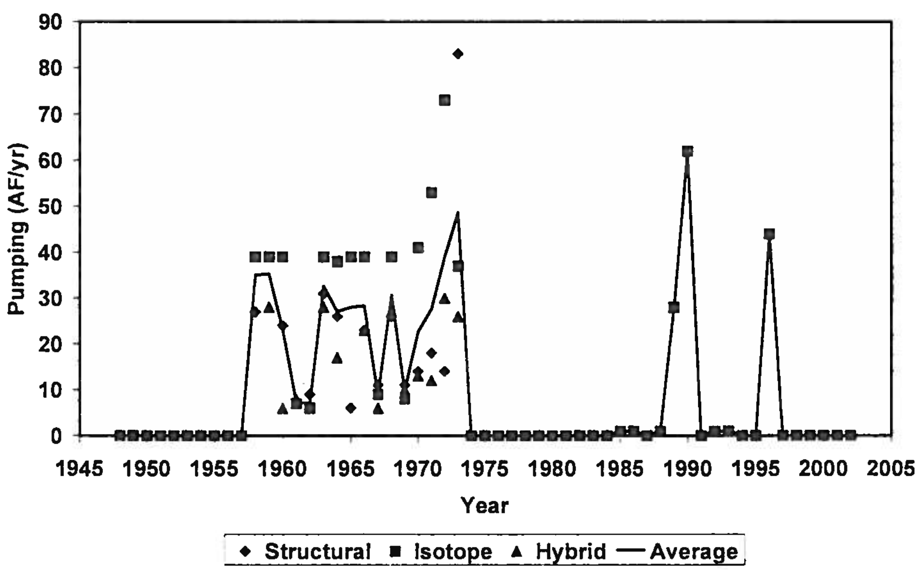
Wilson, John D. and Naff, Richard L., 2004. MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model – GMG Linear Equation Solver Package Documentation. U.S. Geological Survey Open File Report 2004-1261, Reston, Virginia.

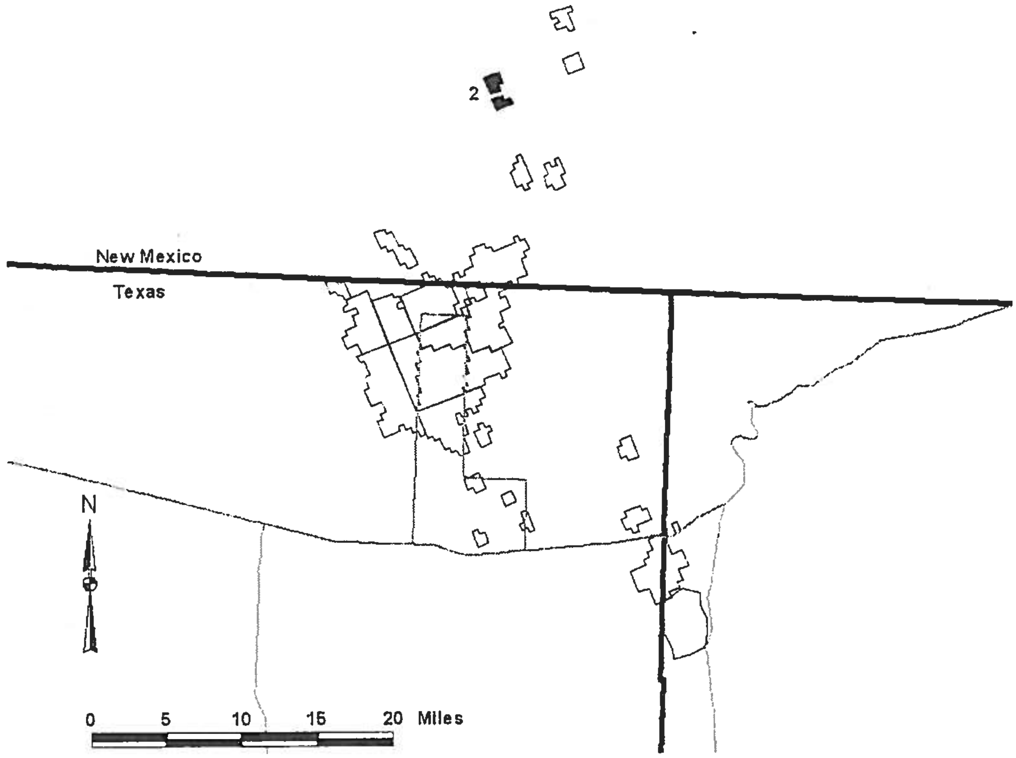
Appendix A

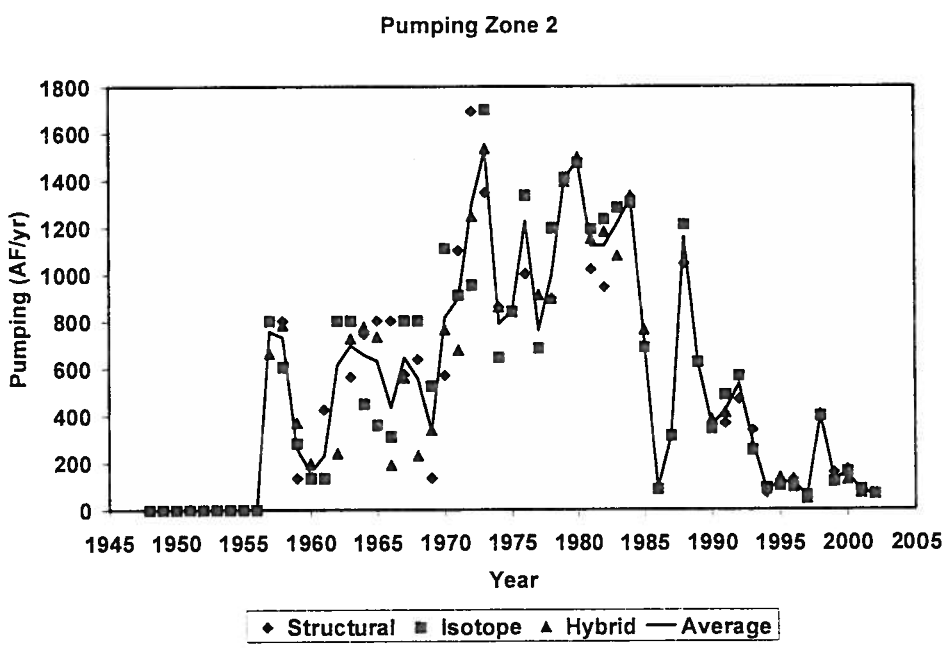
Pumping Estimates for Each Zone

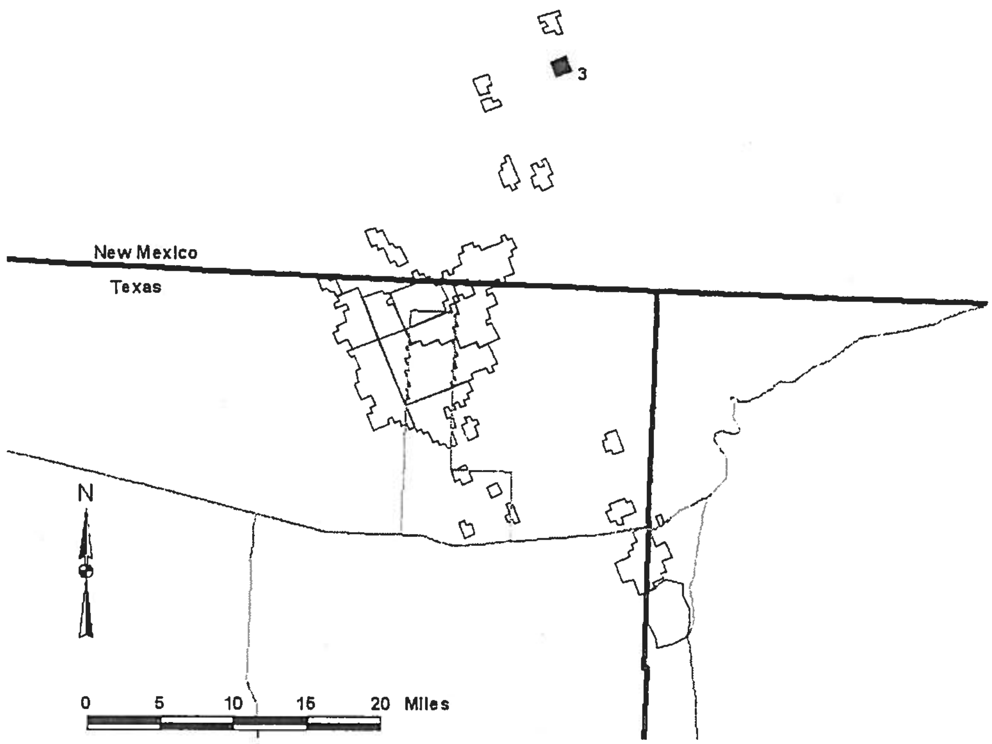


Pumping Zone 1

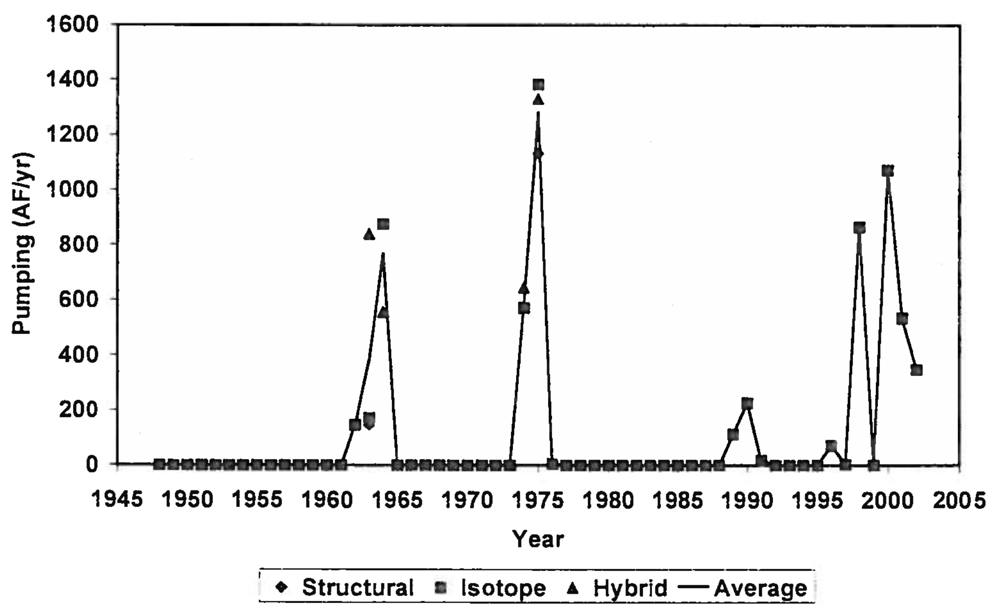


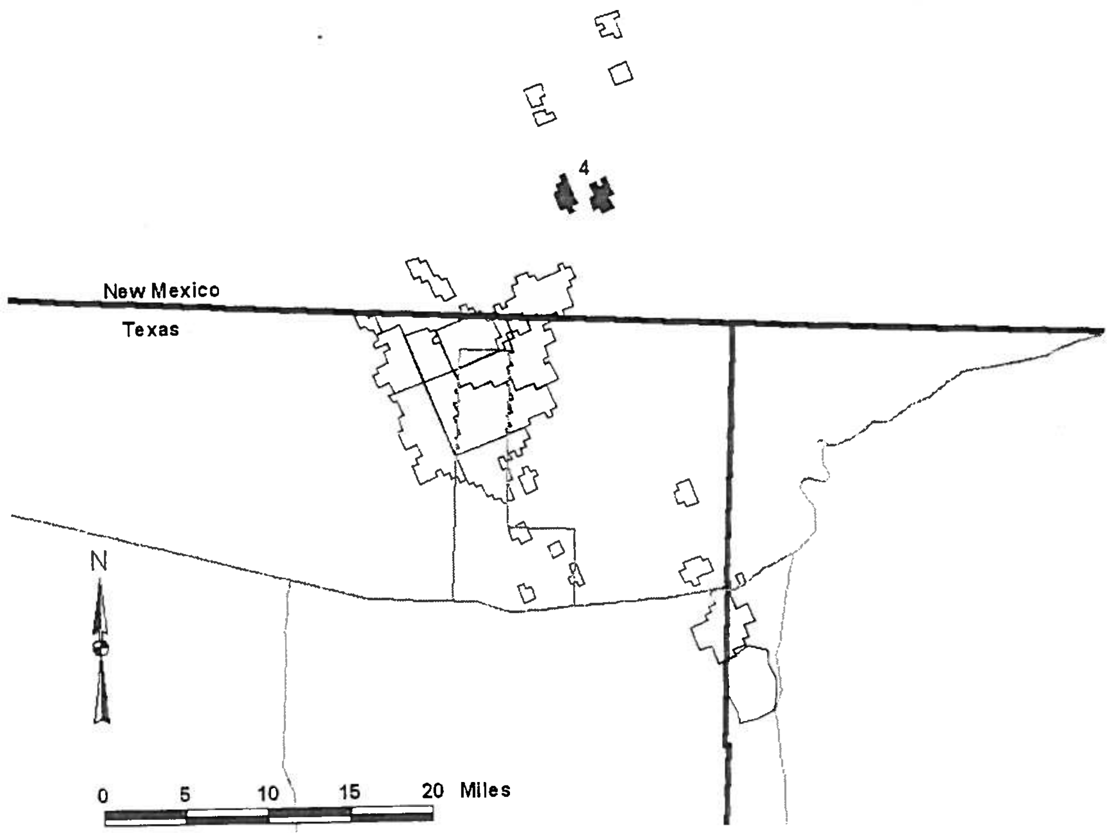

2
New Mexico
Texas
N
0 5 10 15 20 Miles

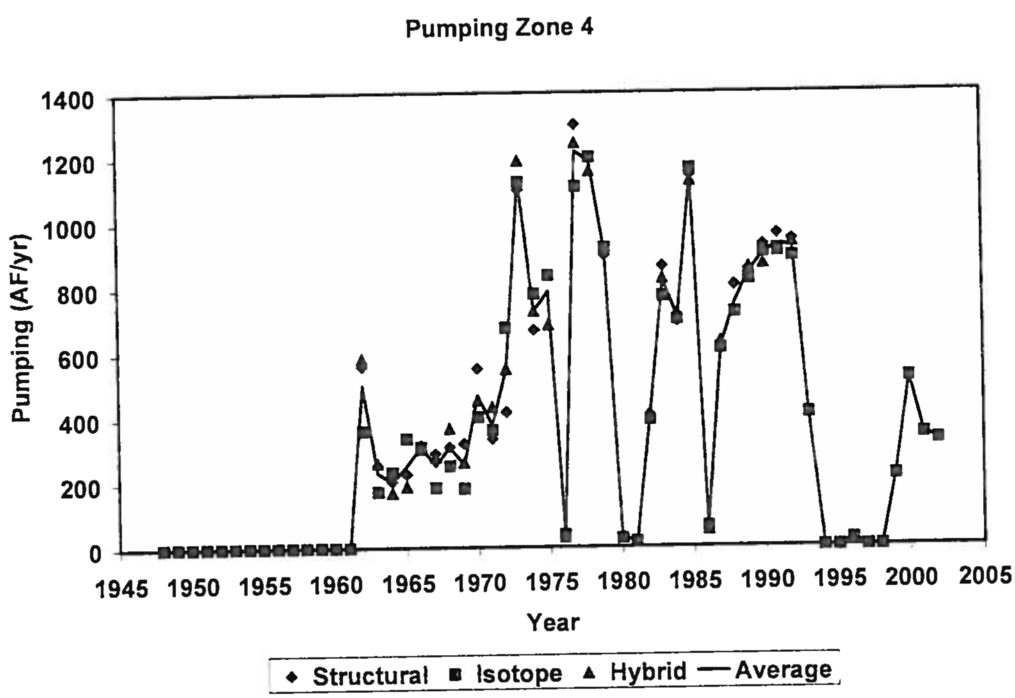

Pumping Zone 2
1800
1600
1400
1200
1000
800
600
400
200
0
Pumping (AF/yr)
1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005
Year
Structural
Isotope
Hybrid
Average

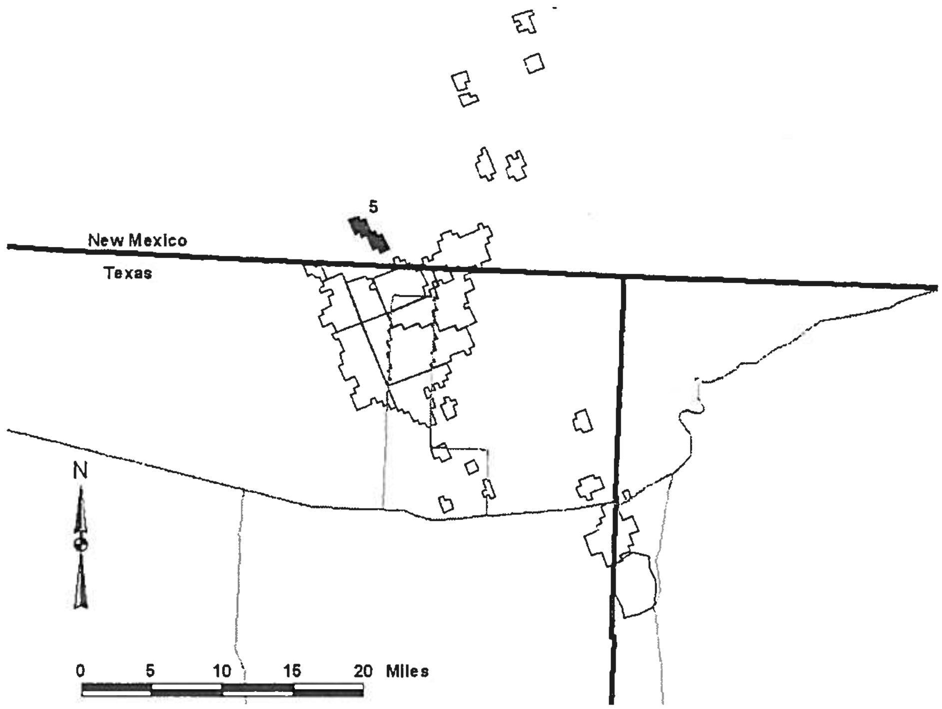


Pumping Zone 3

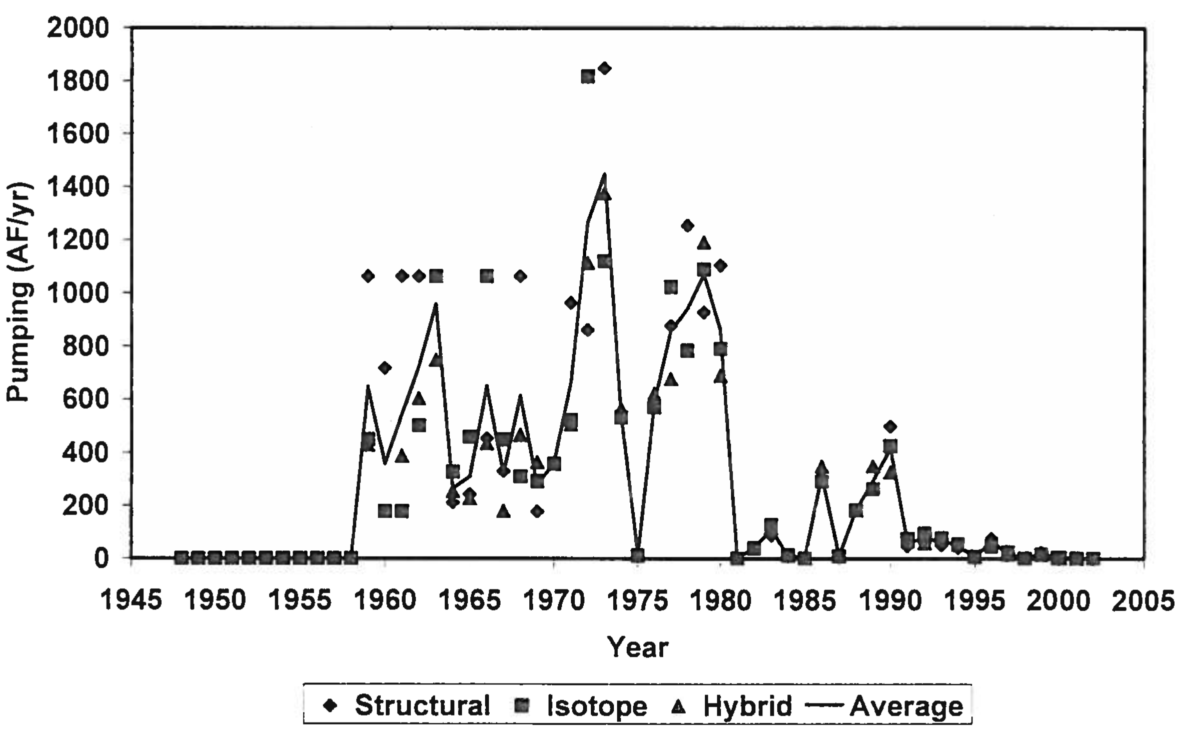


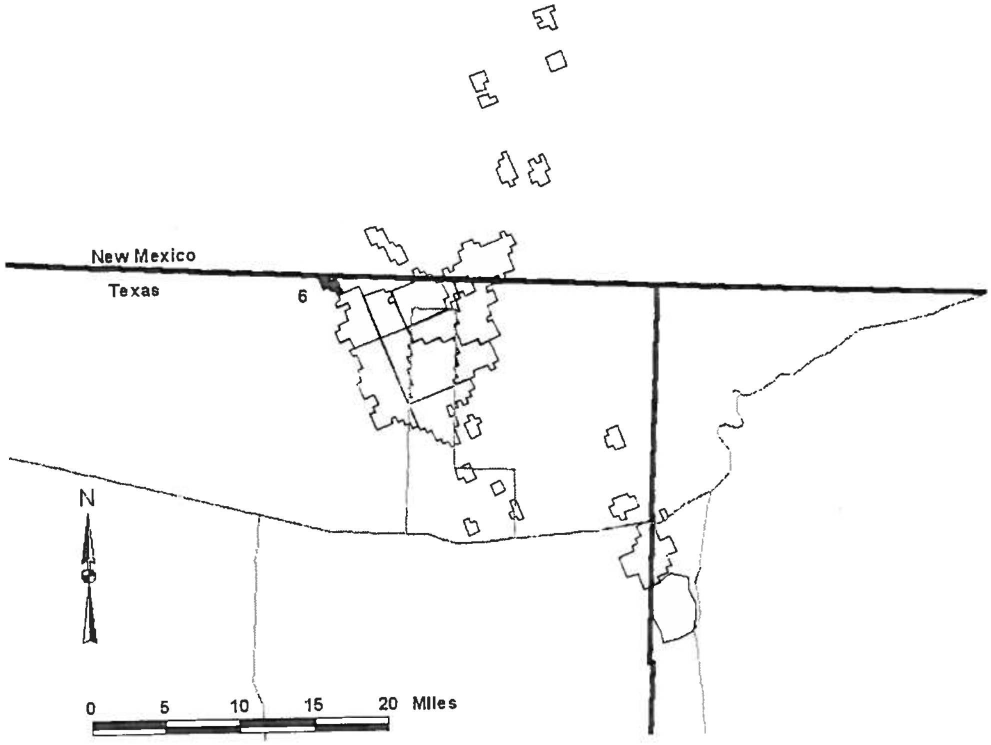

4
New Mexico
Texas
N
0
5
10
15
20 Miles


Pumping Zone 4
1400
1200
1000
800
600
400
200
0
Pumping (AF/yr)
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year
Structural
Isotope
Hybrid
Average

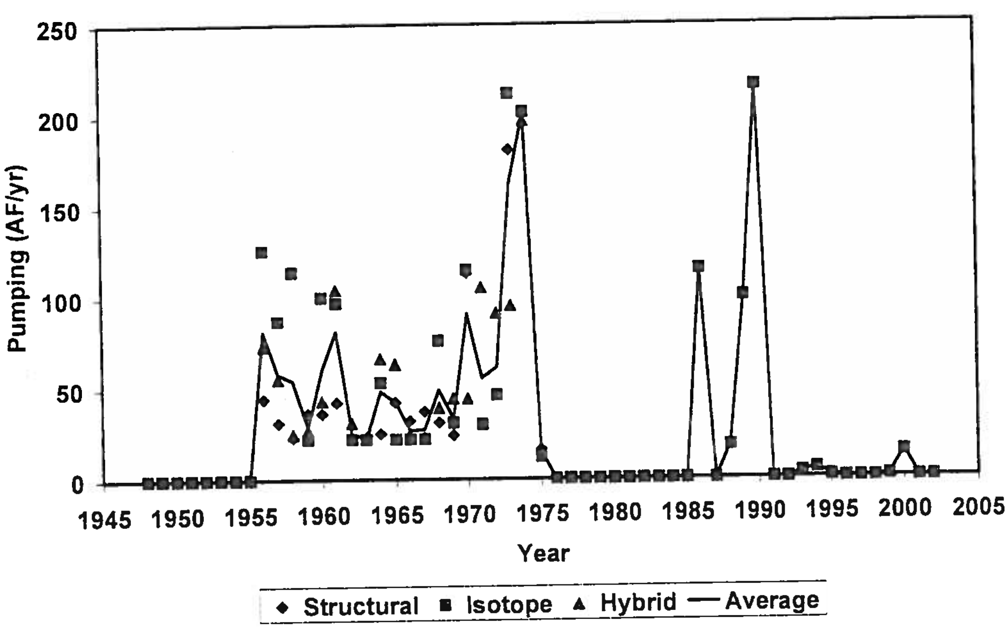


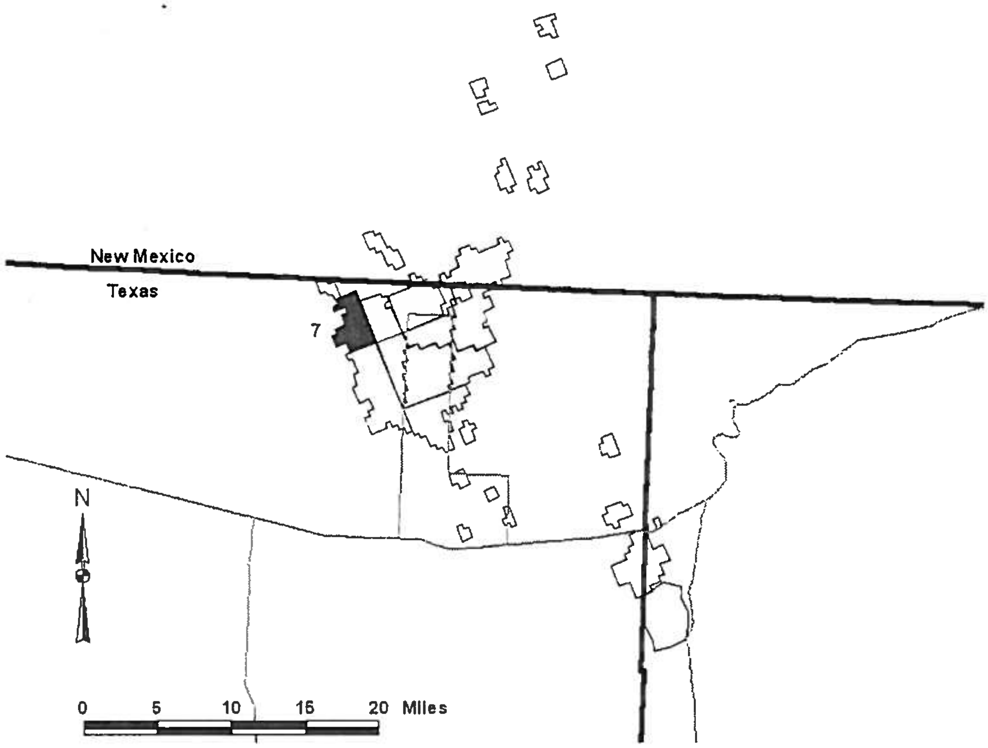
Pumping Zone 5

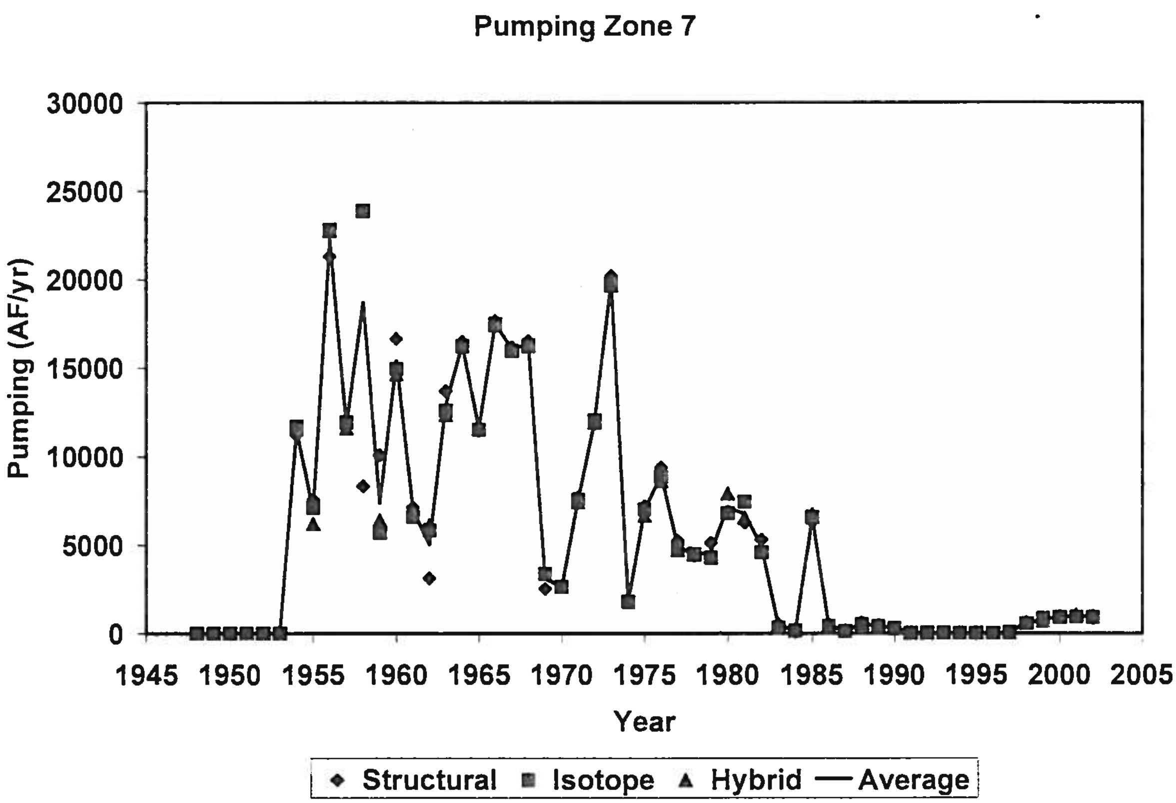


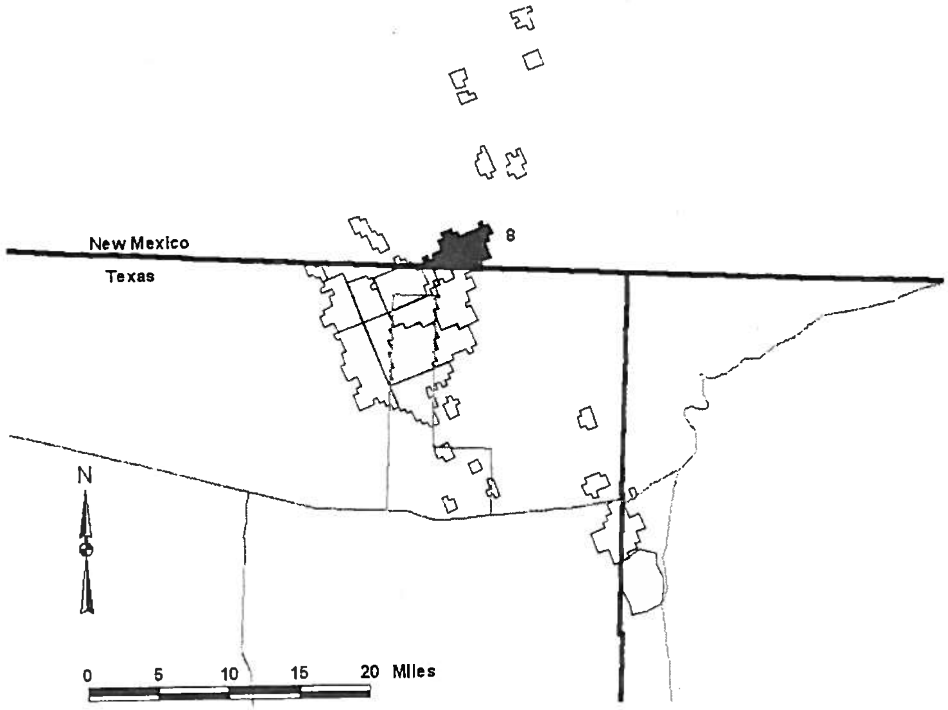


Pumping Zone 6

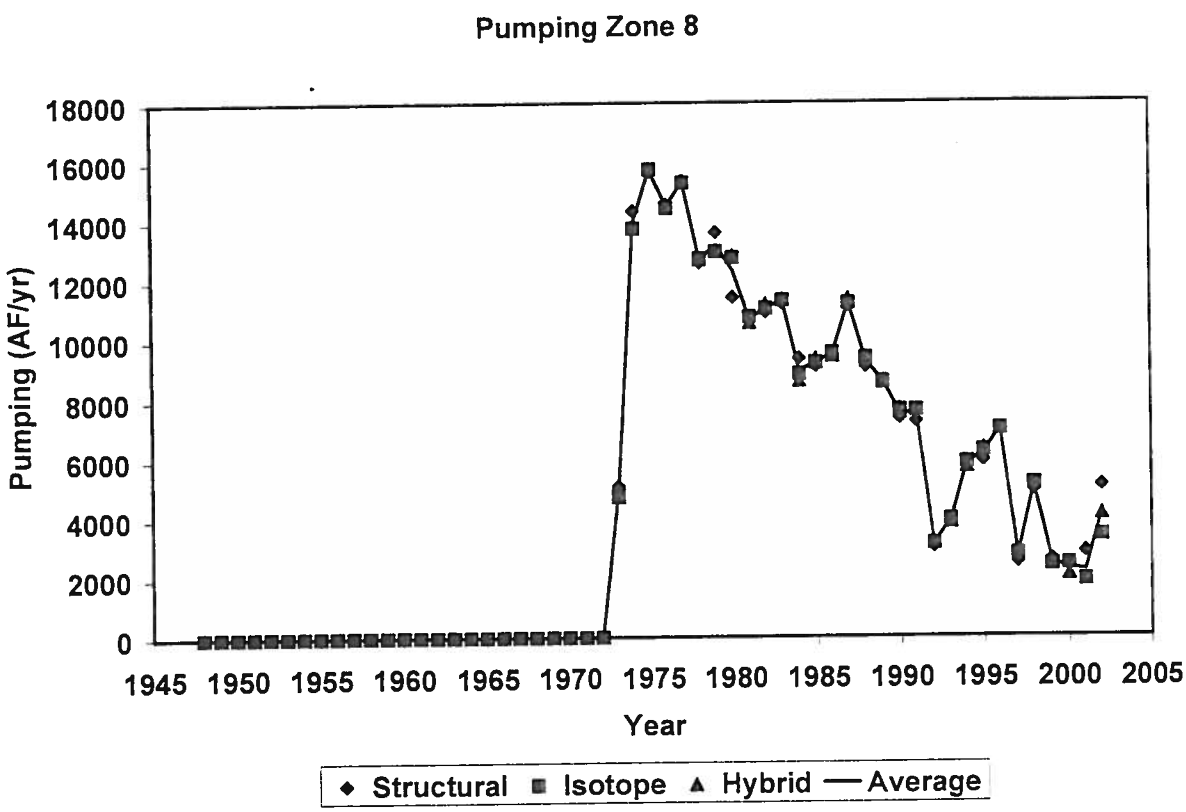



New Mexico
Texas
7
N
0 5 10 15 20 Miles

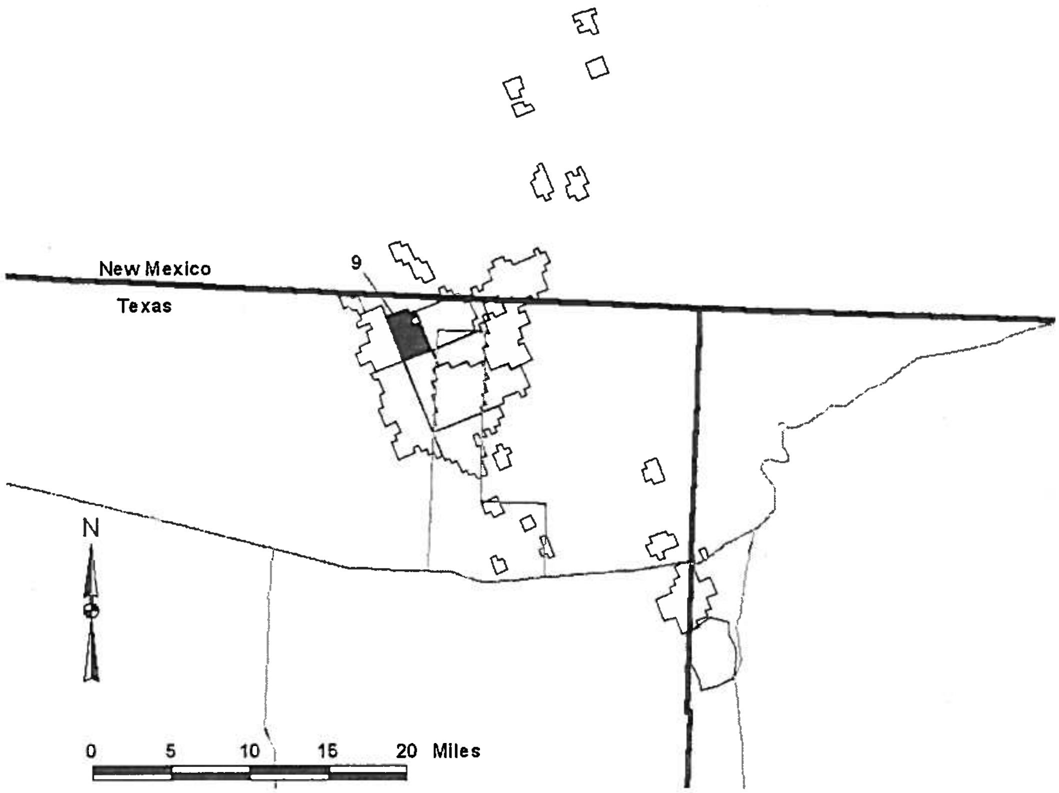

Pumping Zone 7
30000
25000
20000
15000
10000
5000
0
Pumping (AF/yr)
1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005
Year
Structural Isotope Hybrid Average



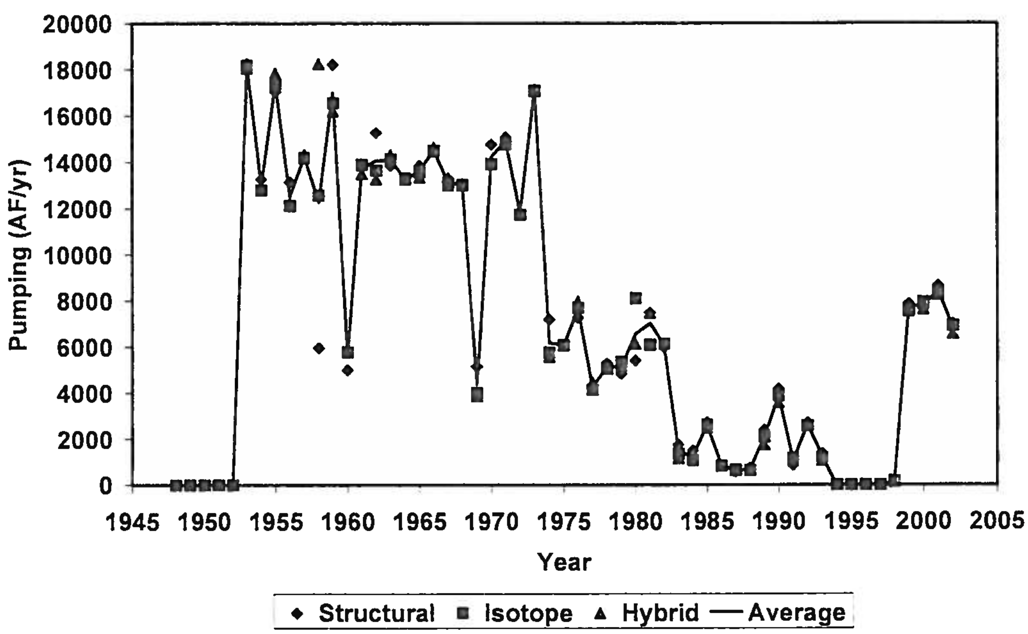
8
New Mexico
Texas
N
0 5 10 15 20 Miles

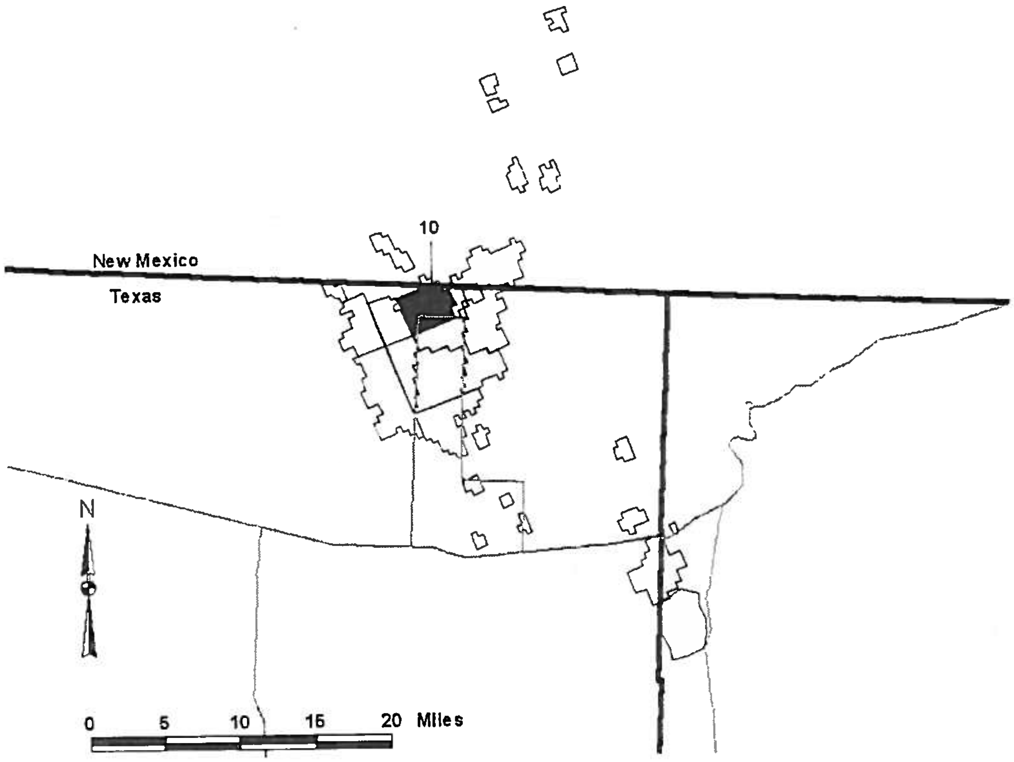


Pumping Zone 8
Pumping (AF/yr)
Year
Structural
Isotope
Hybrid
Average

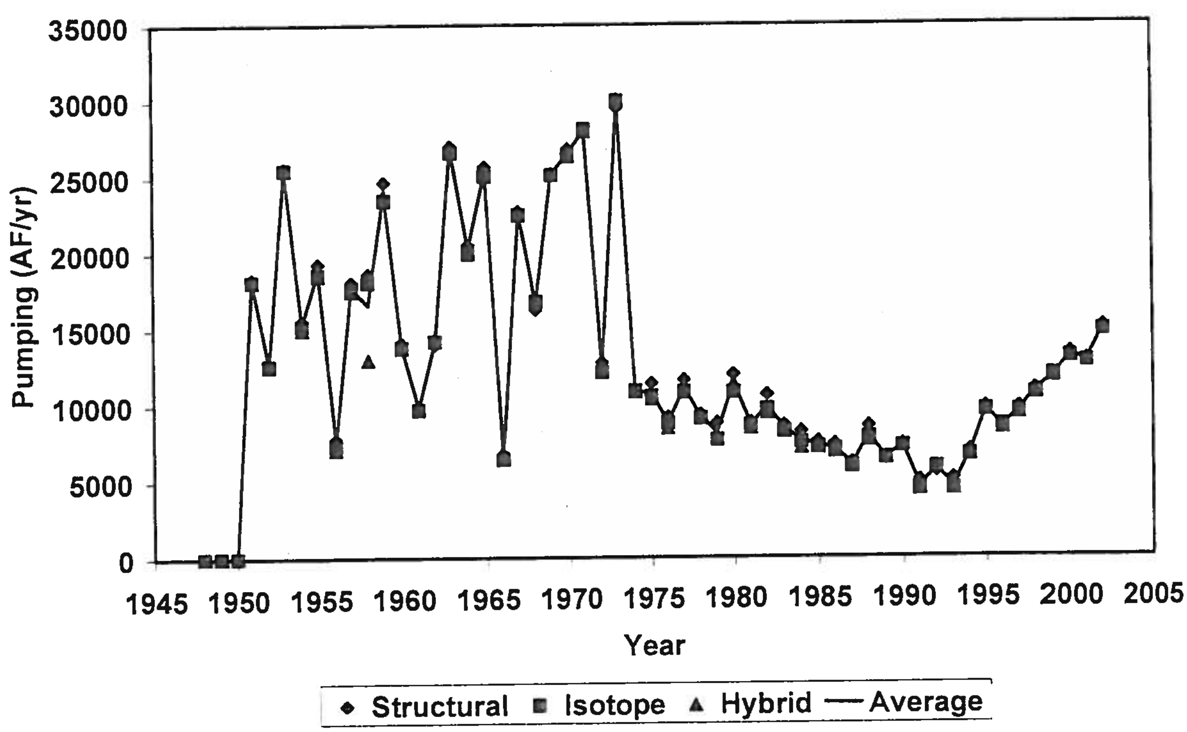


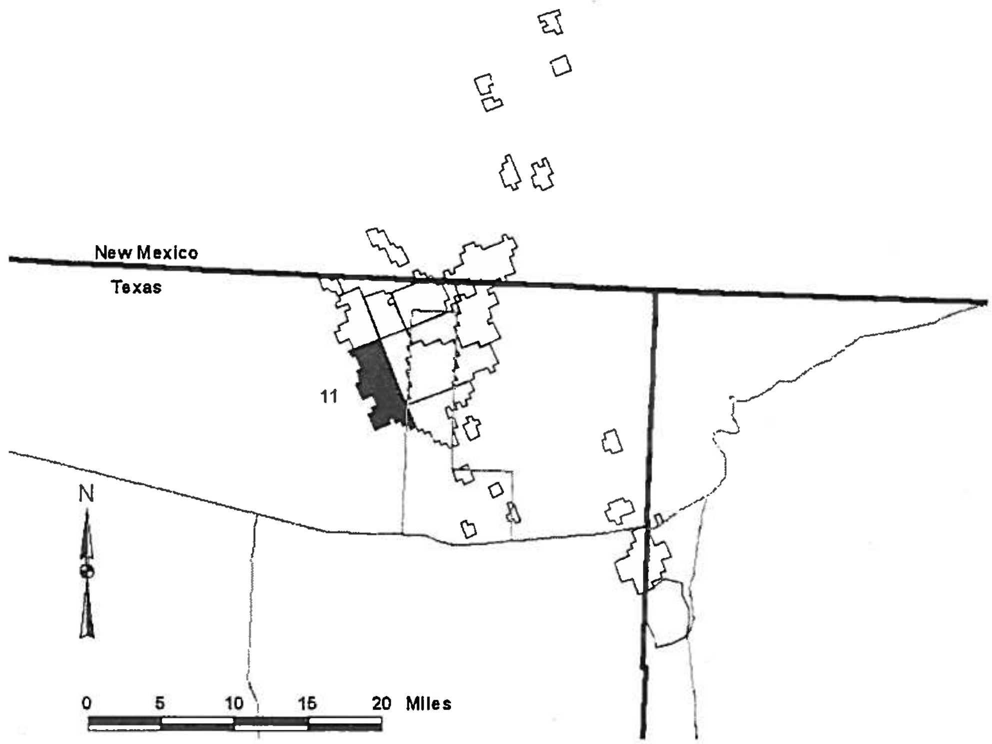
Pumping Zone 9



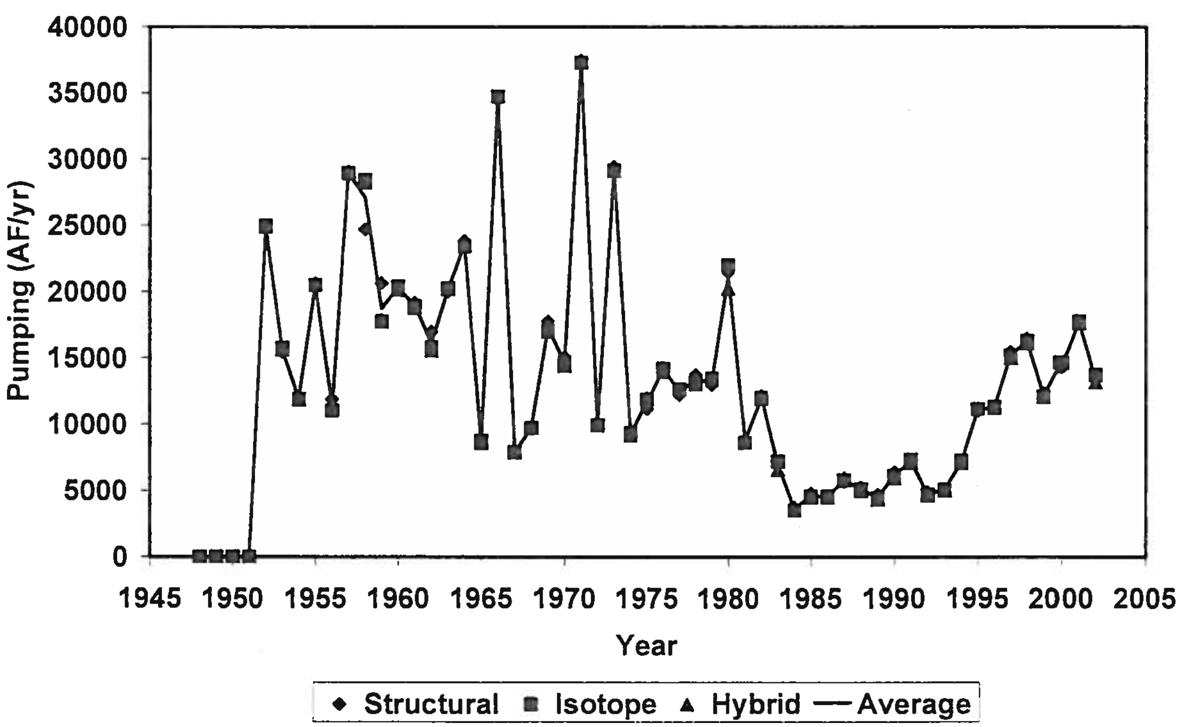


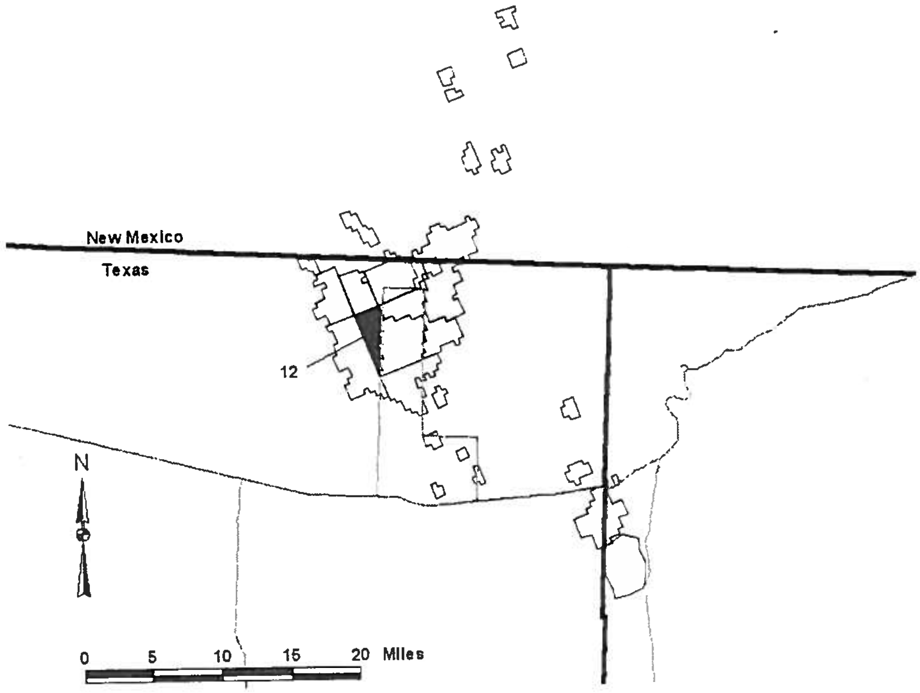
Pumping Zone 10



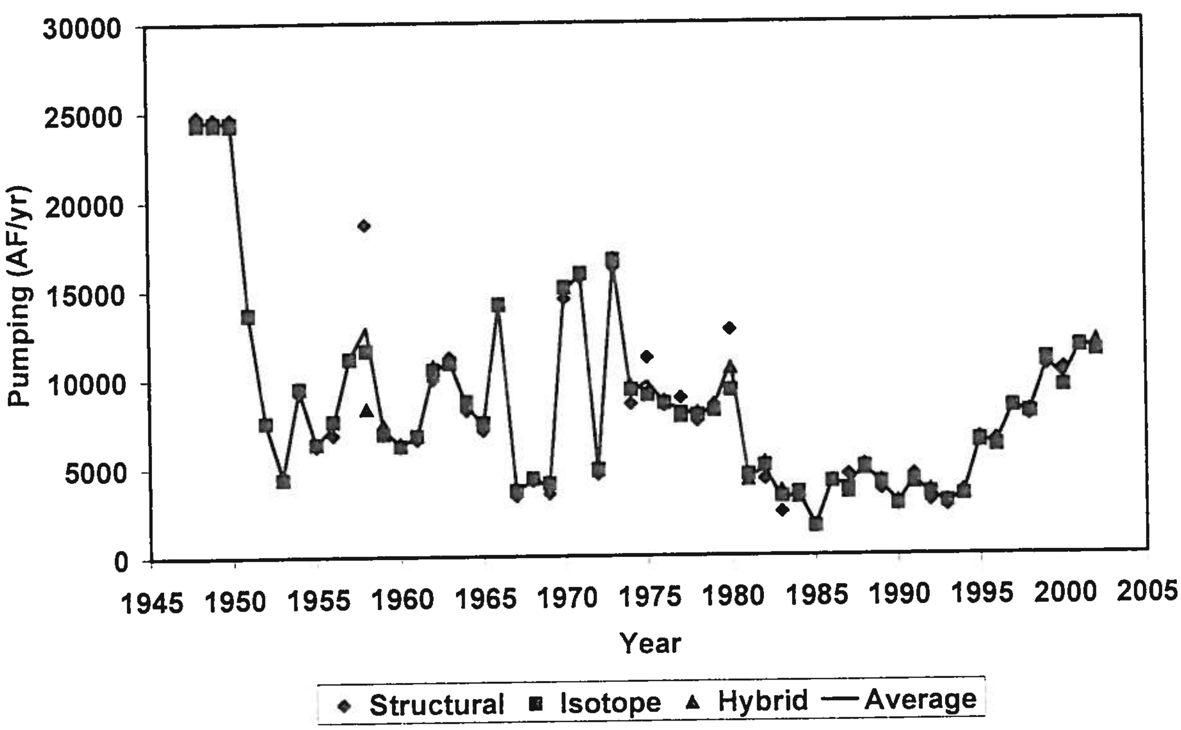


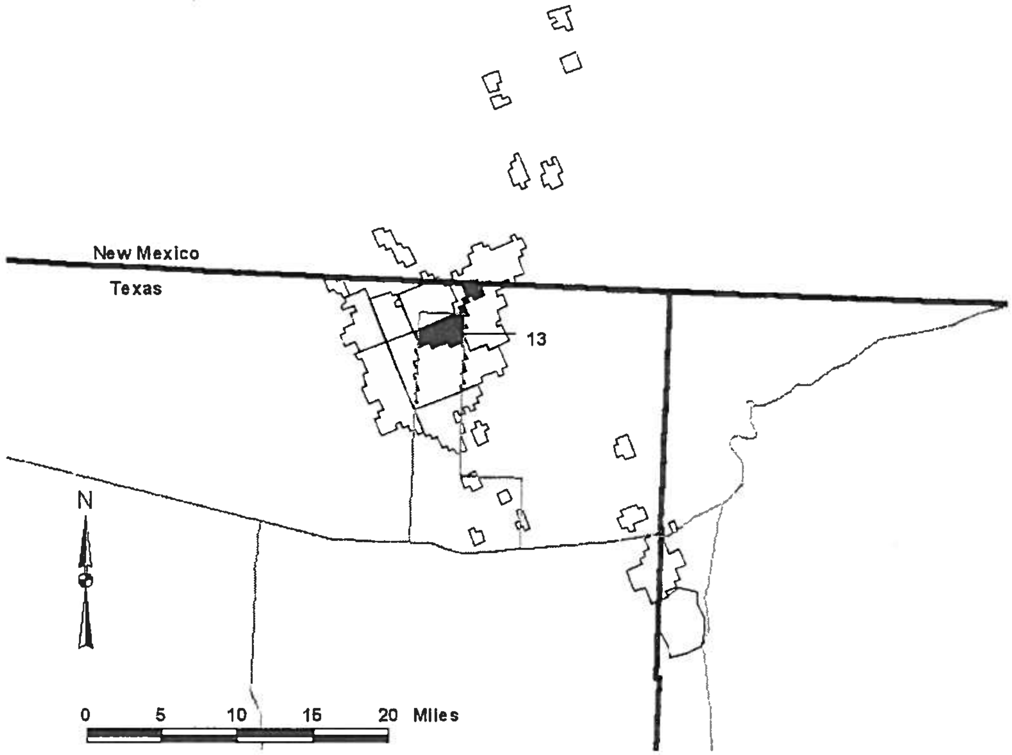
Pumping Zone 11



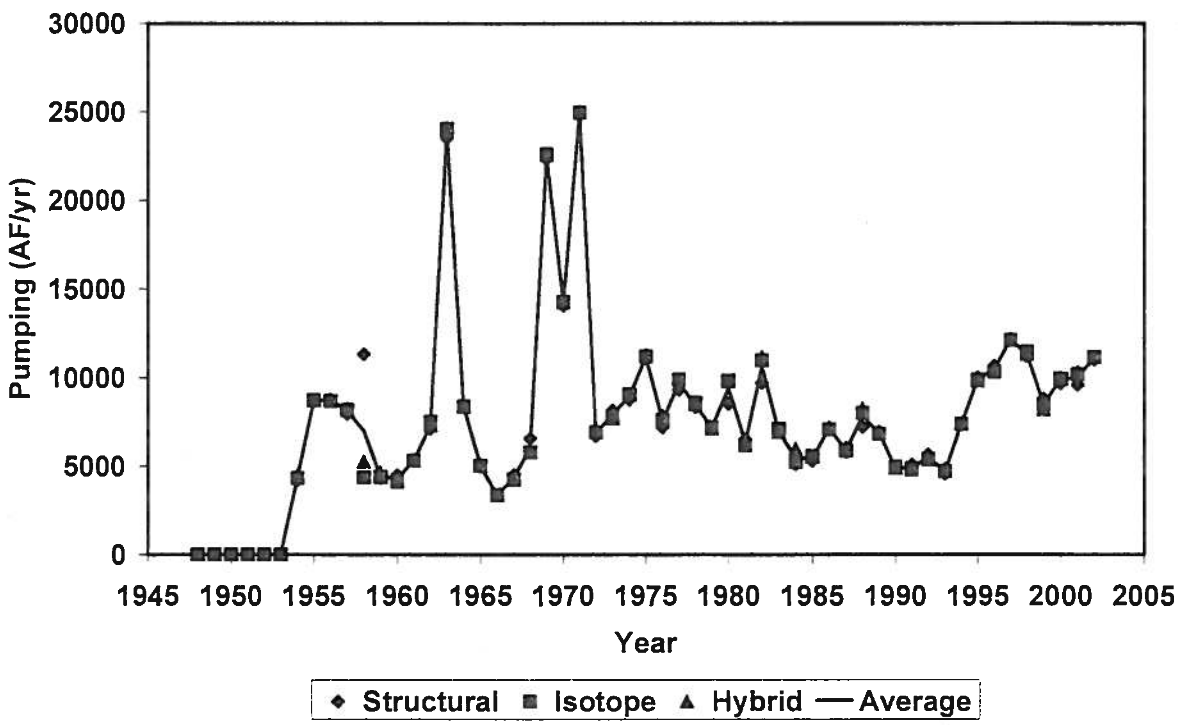


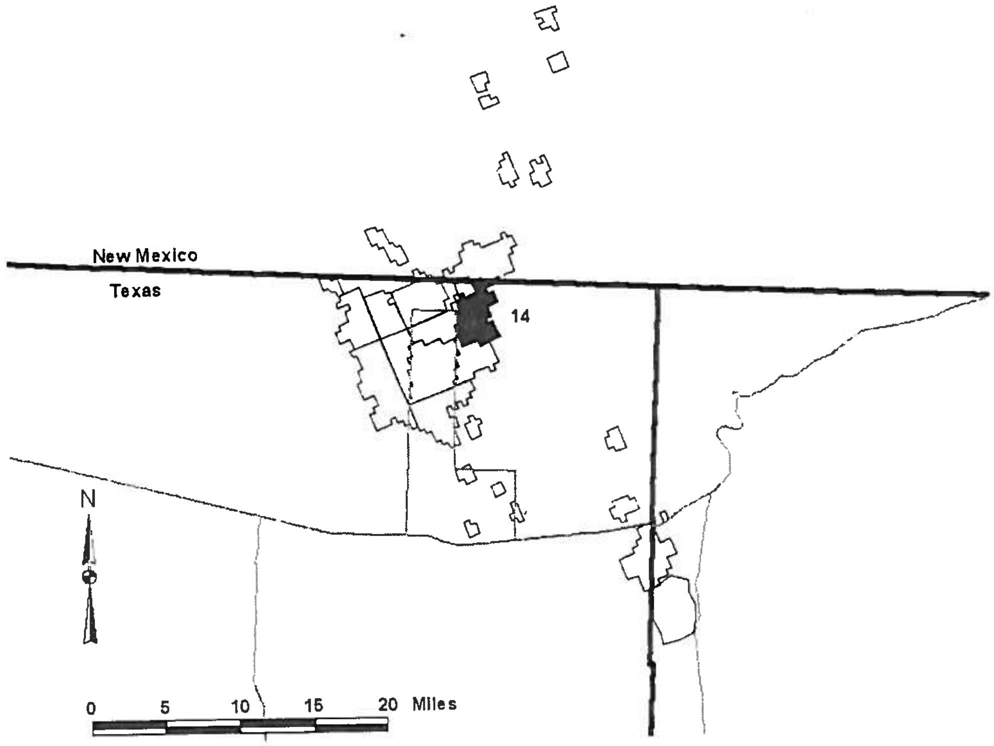
Pumping Zone 12



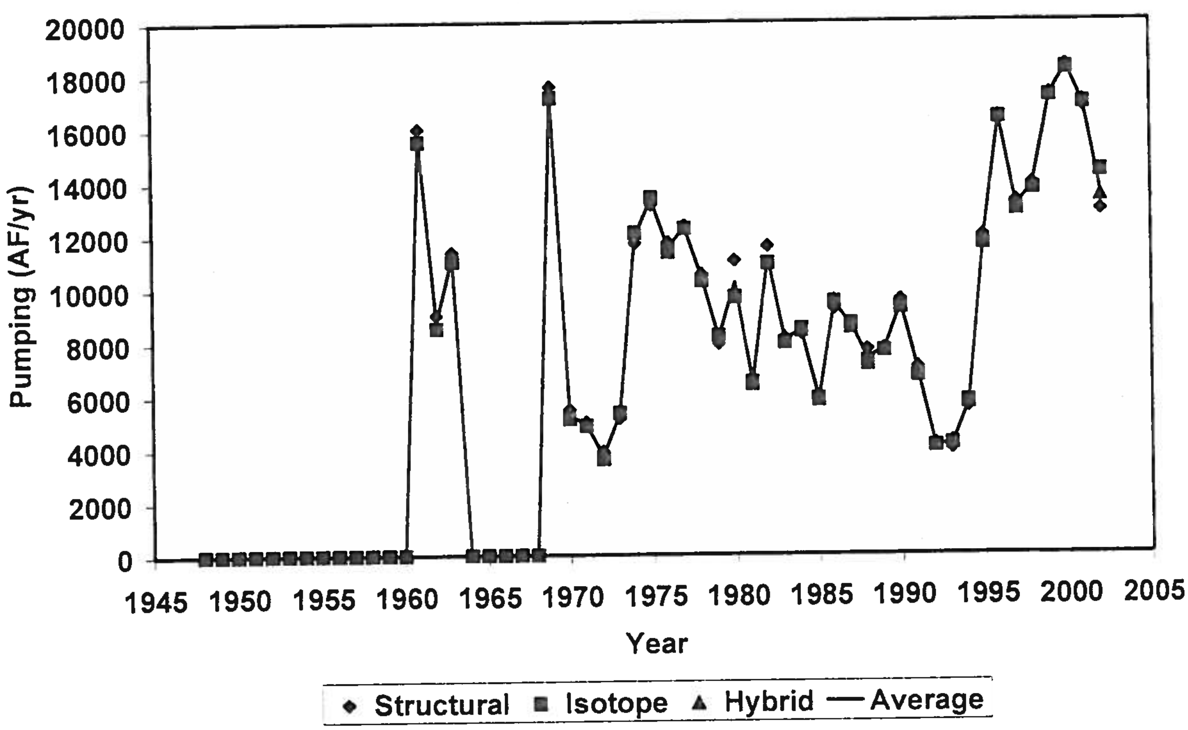


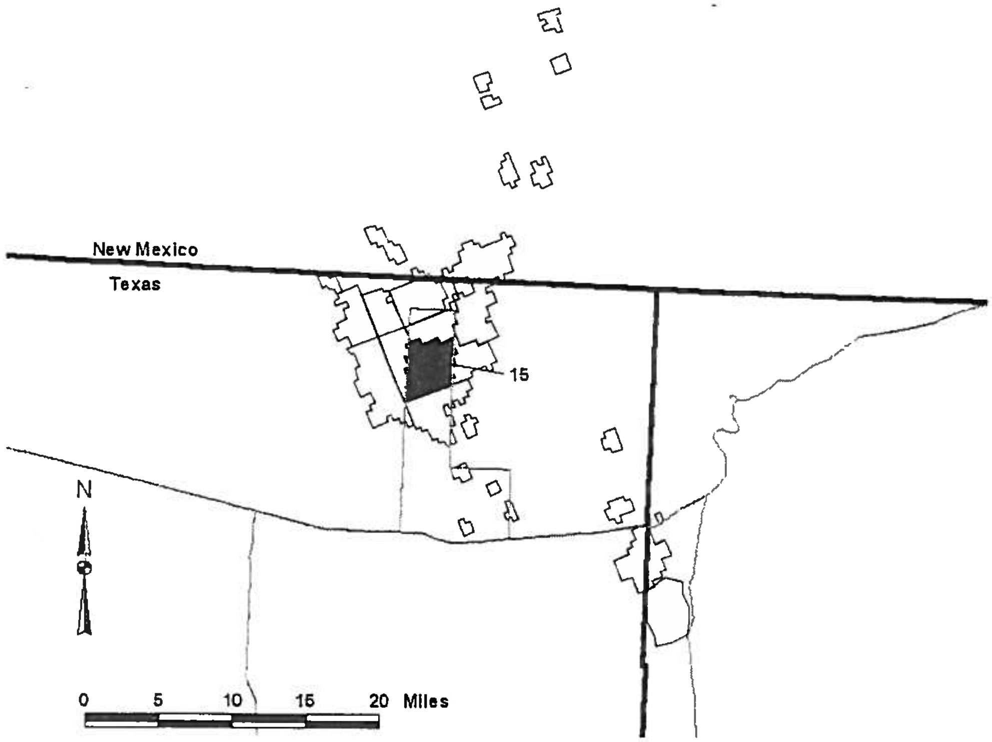
Pumping Zone 13



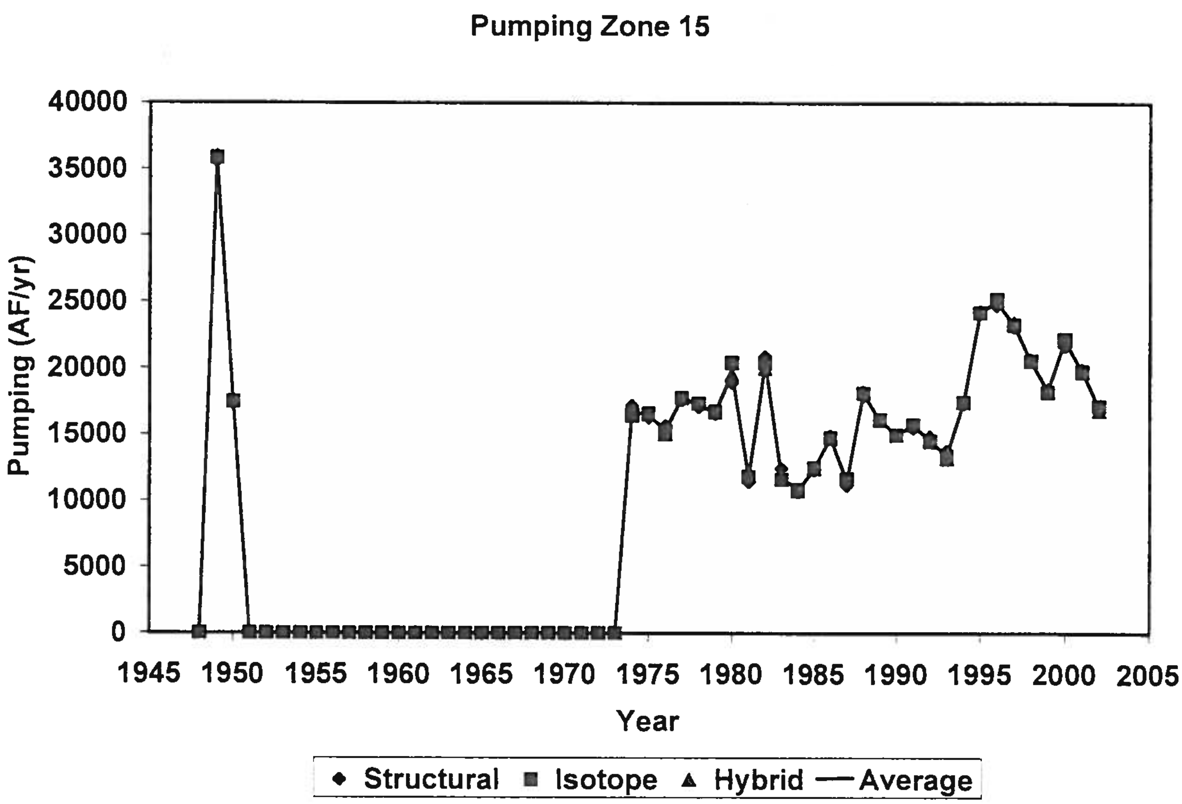


Pumping Zone 14

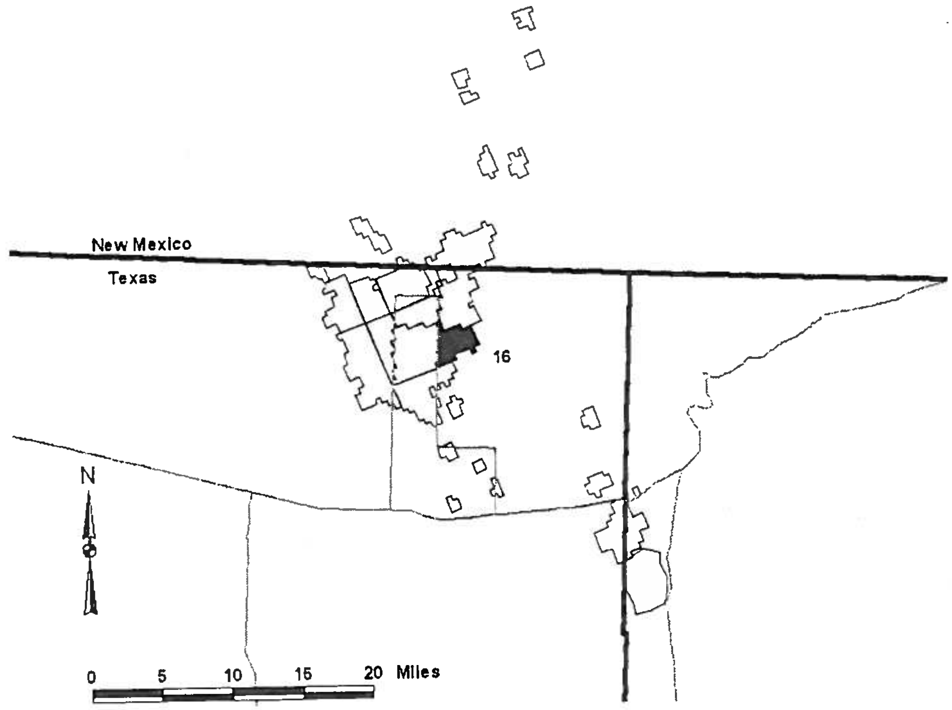




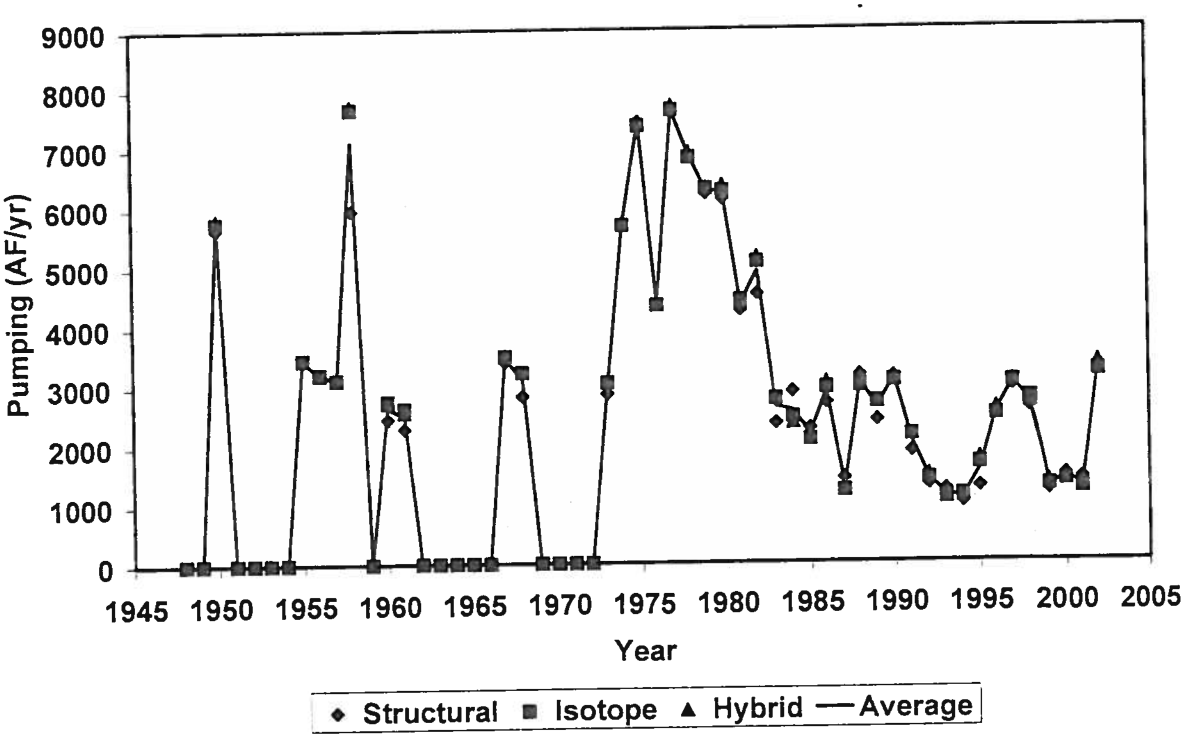
New Mexico
Texas
15
N
0 5 10 15 20 Miles

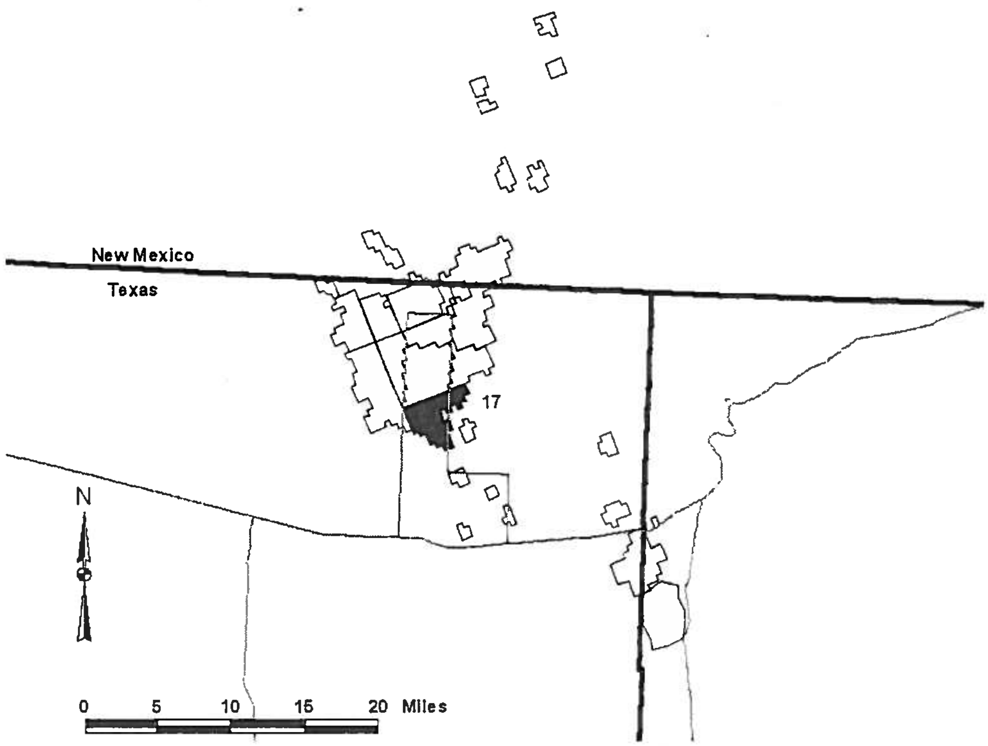


Pumping Zone 15
Pumping (AF/yr)
40000
35000
30000
25000
20000
15000
10000
5000
0
1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005
Year
◆ Structural ■ Isotope ▲ Hybrid — Average

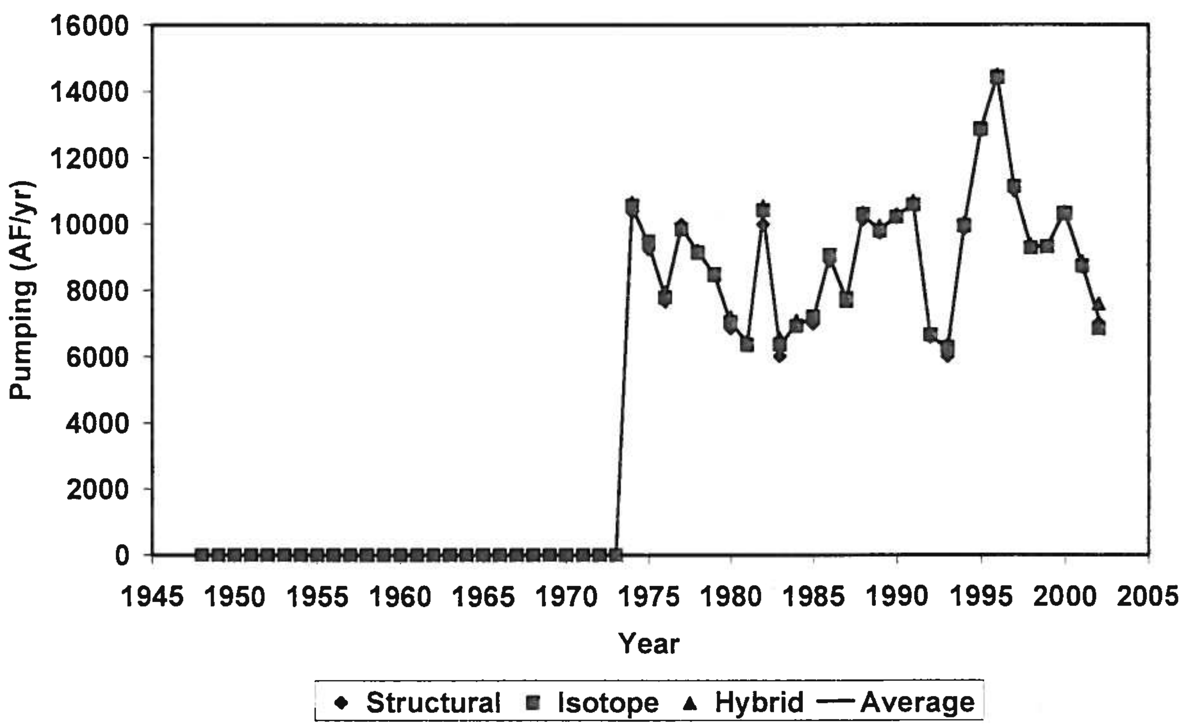


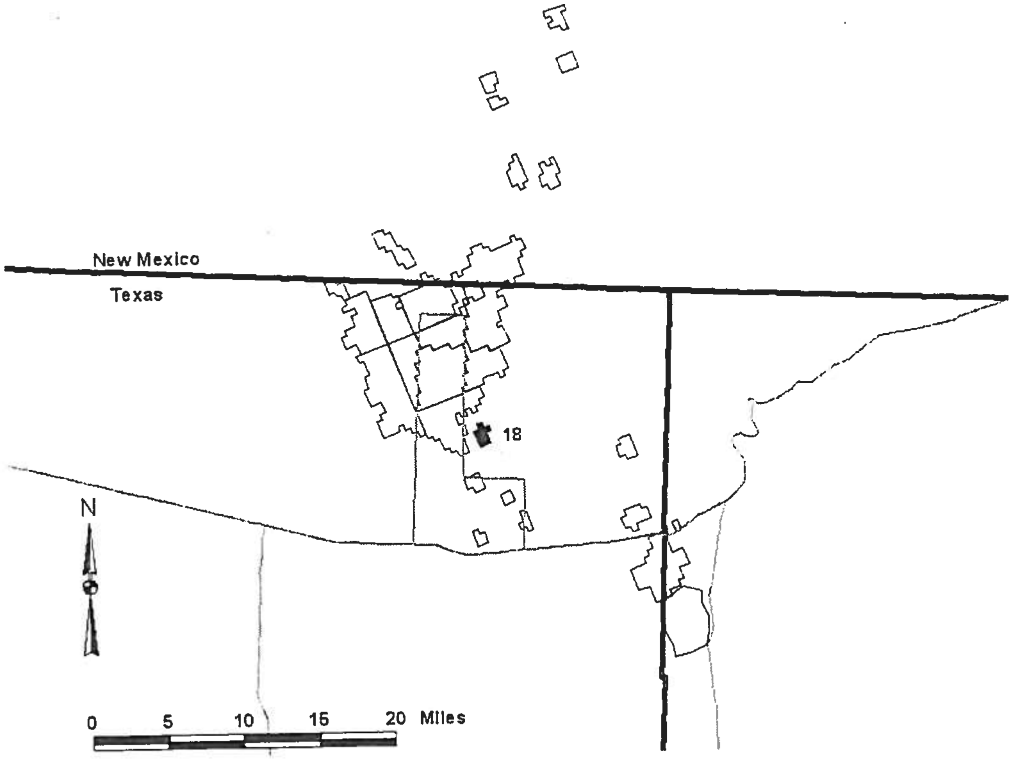
Pumping Zone 16



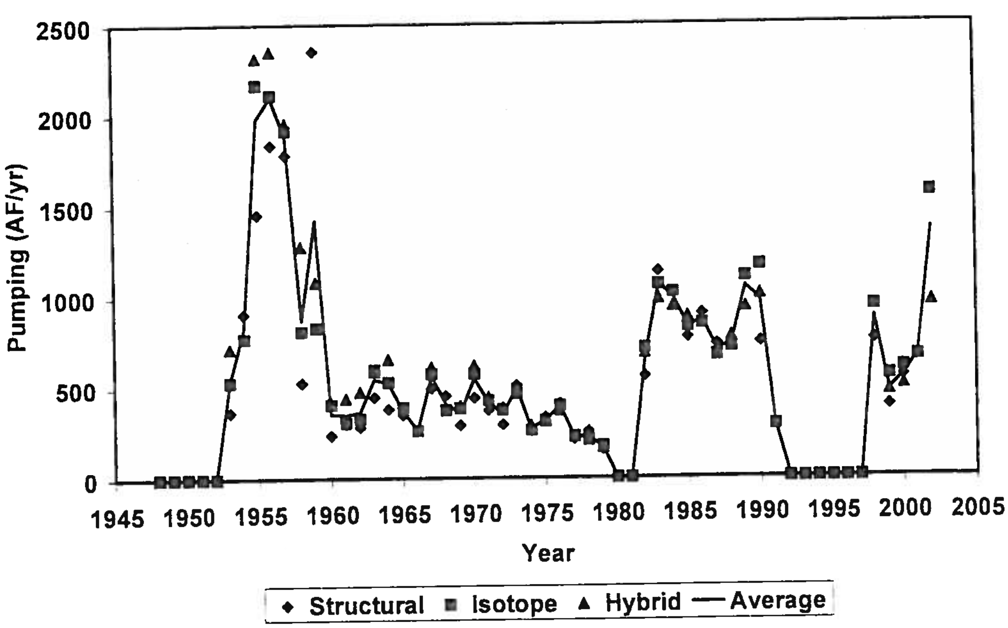


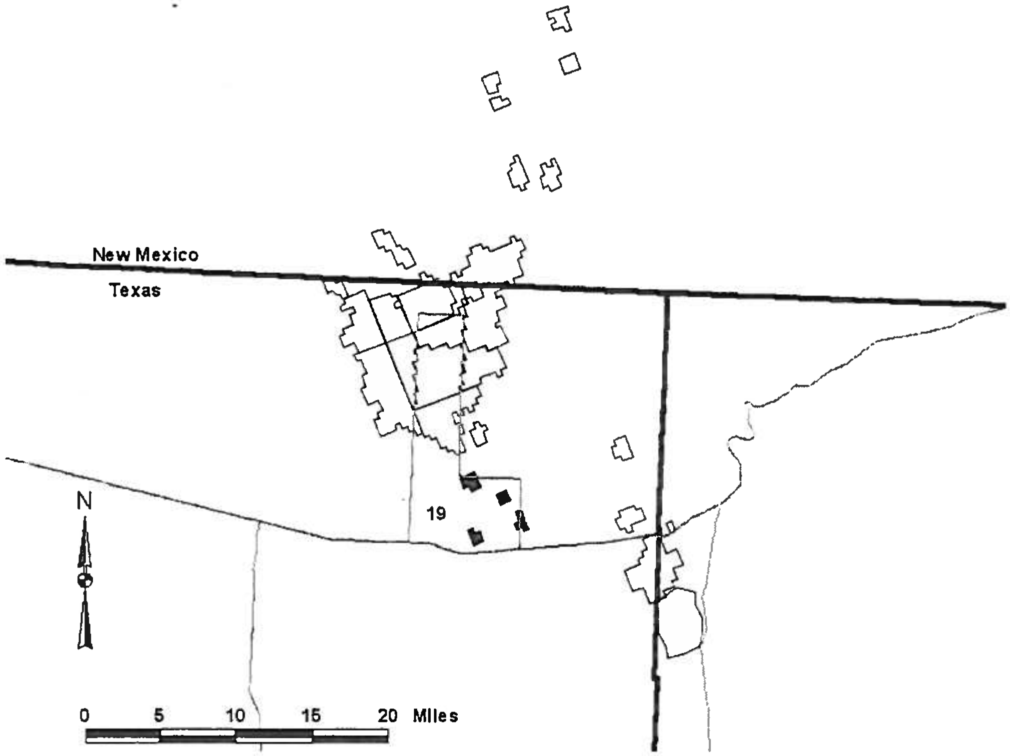
Pumping Zone 17

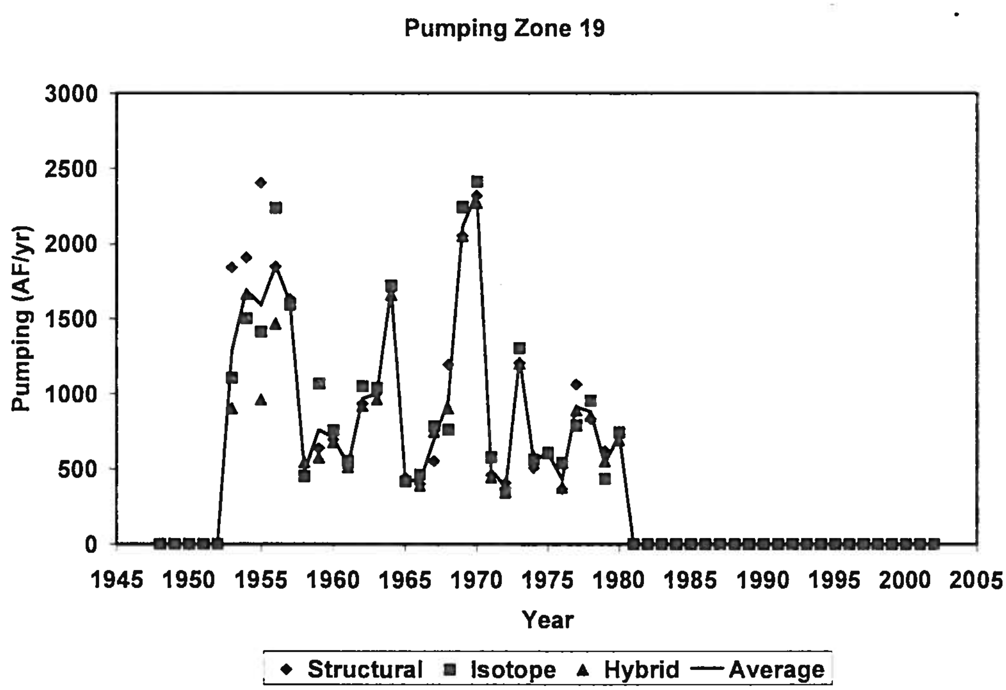


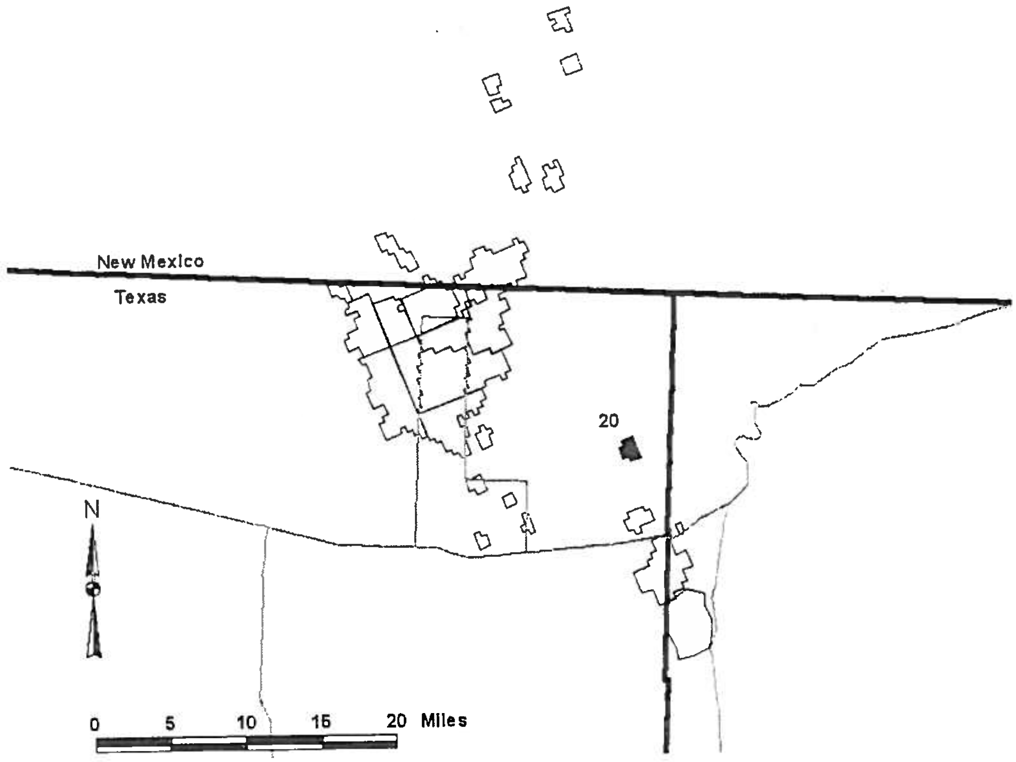


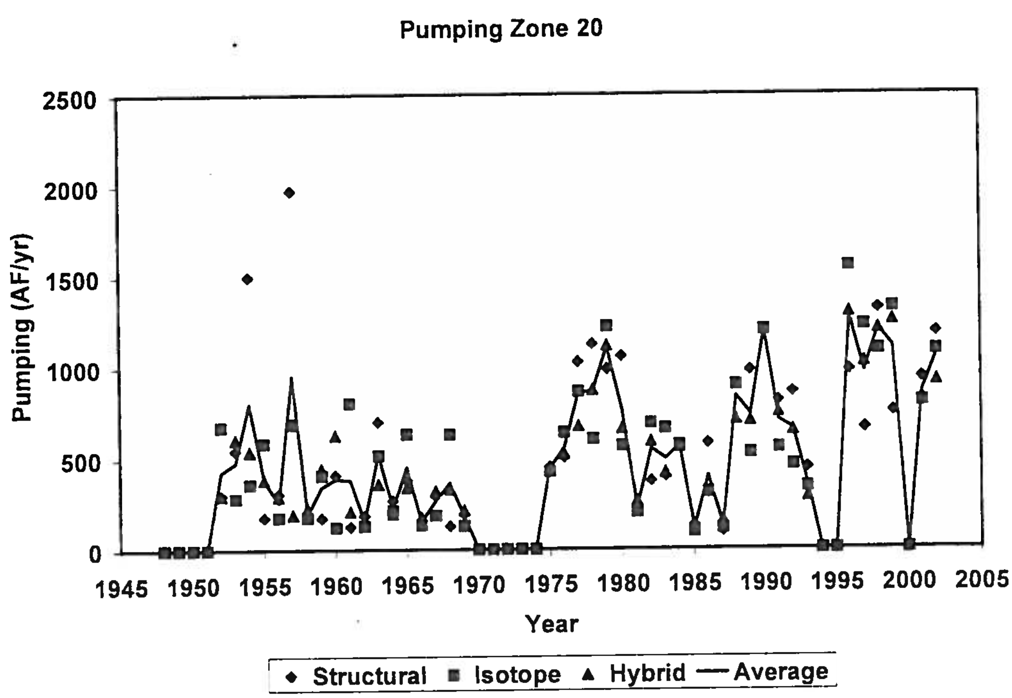
Pumping Zone 18

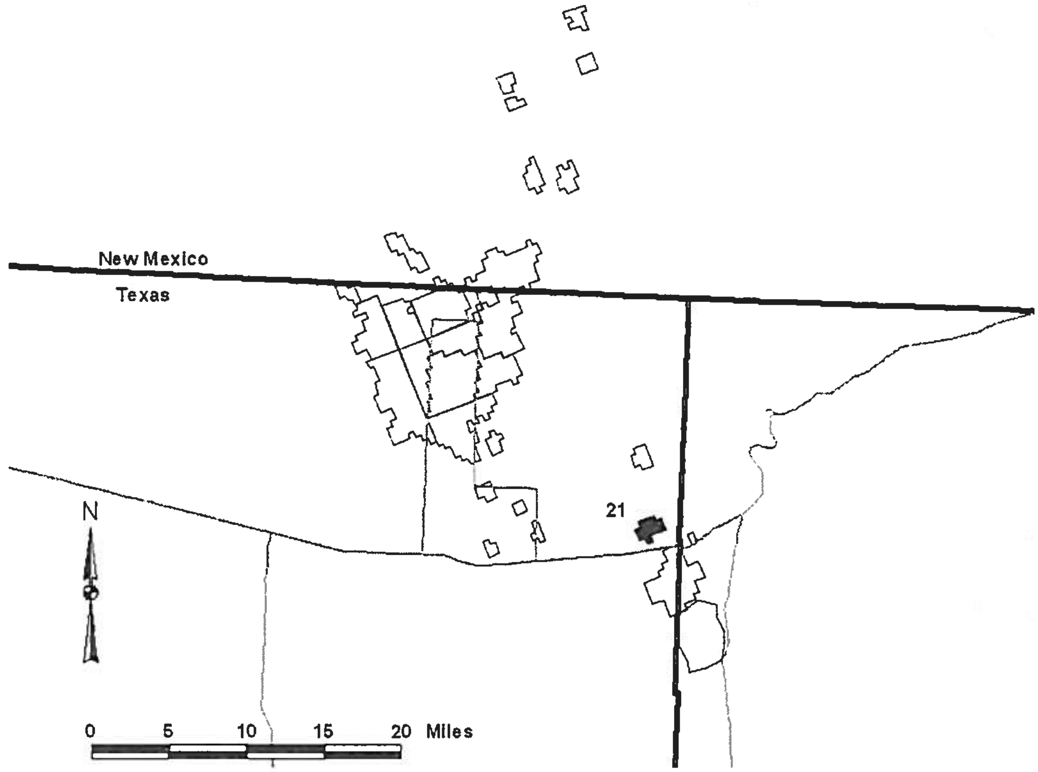



New Mexico
Texas
19
N
0 5 10 15 20 Miles

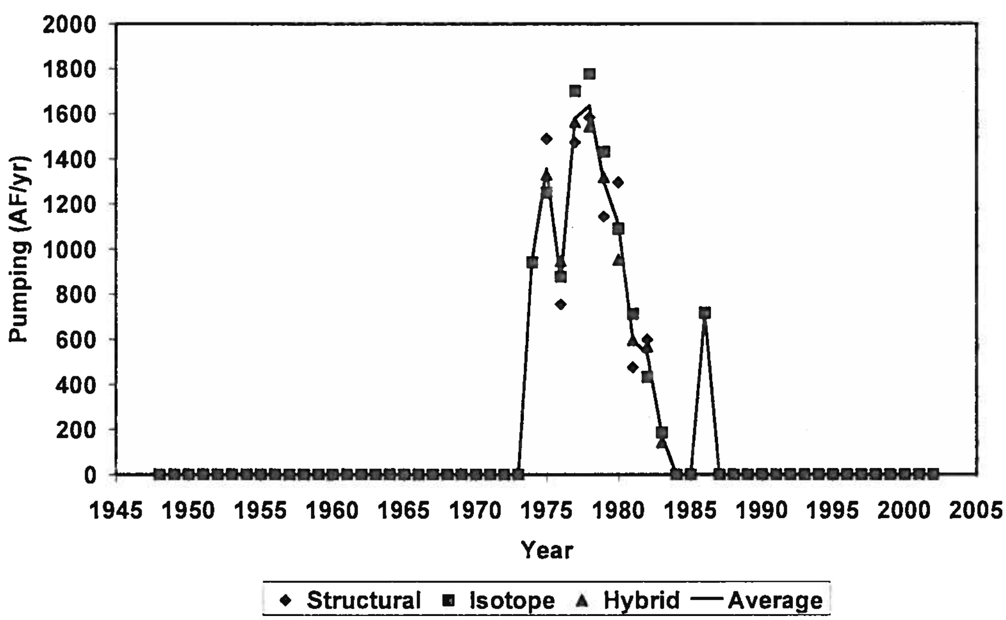

Pumping Zone 19
Pumping (AF/yr)
3000
2500
2000
1500
1000
500
0
1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005
Year
Structural
Isotope
Hybrid
Average

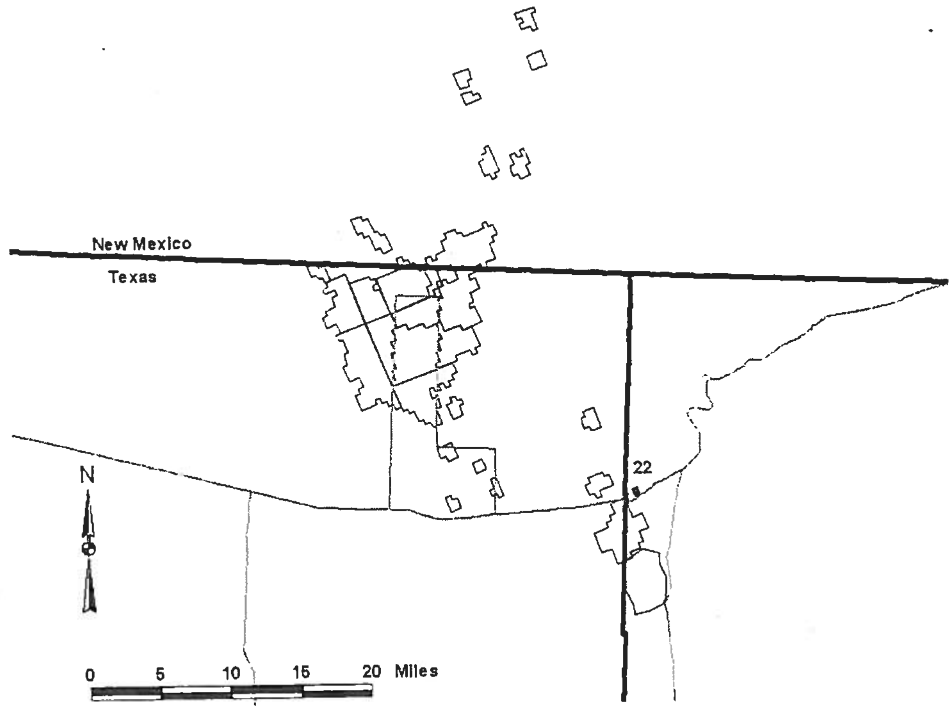

New Mexico
Texas
20
N
0 5 10 15 20 Miles


Pumping Zone 20
2500
2000
1500
1000
500
0
Pumping (AF/yr)
1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005
Year
Structural
Isotope
Hybrid
Average

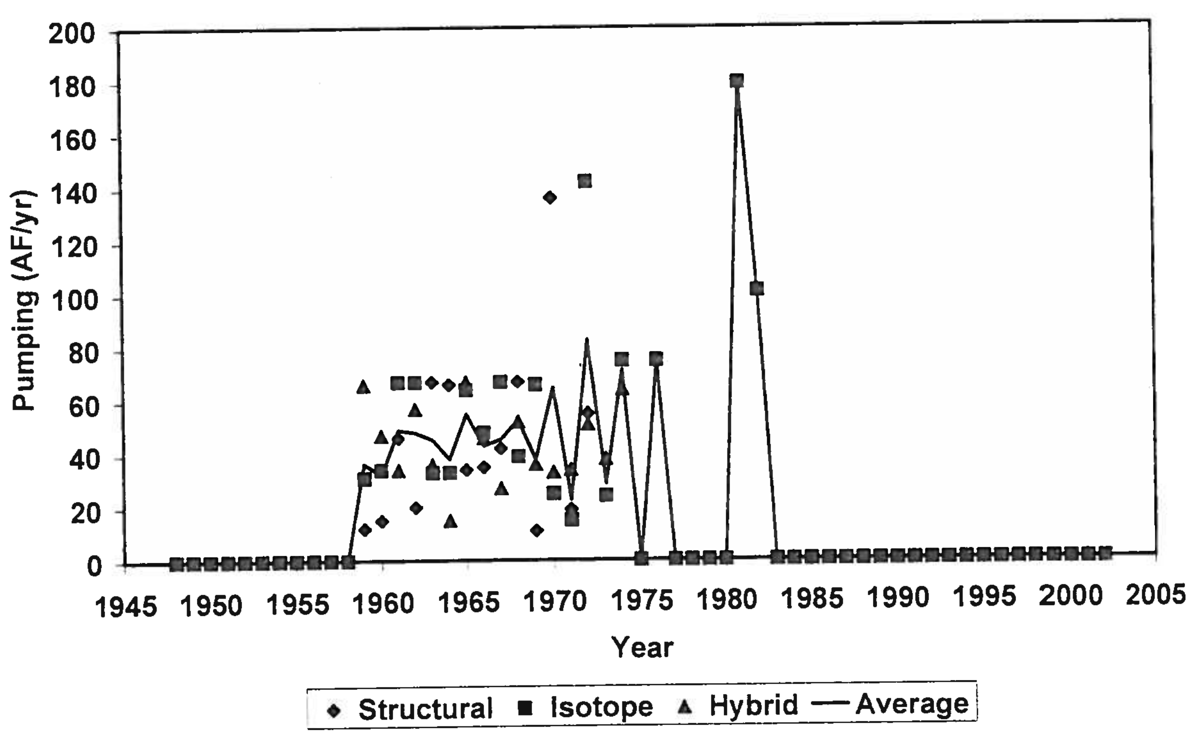


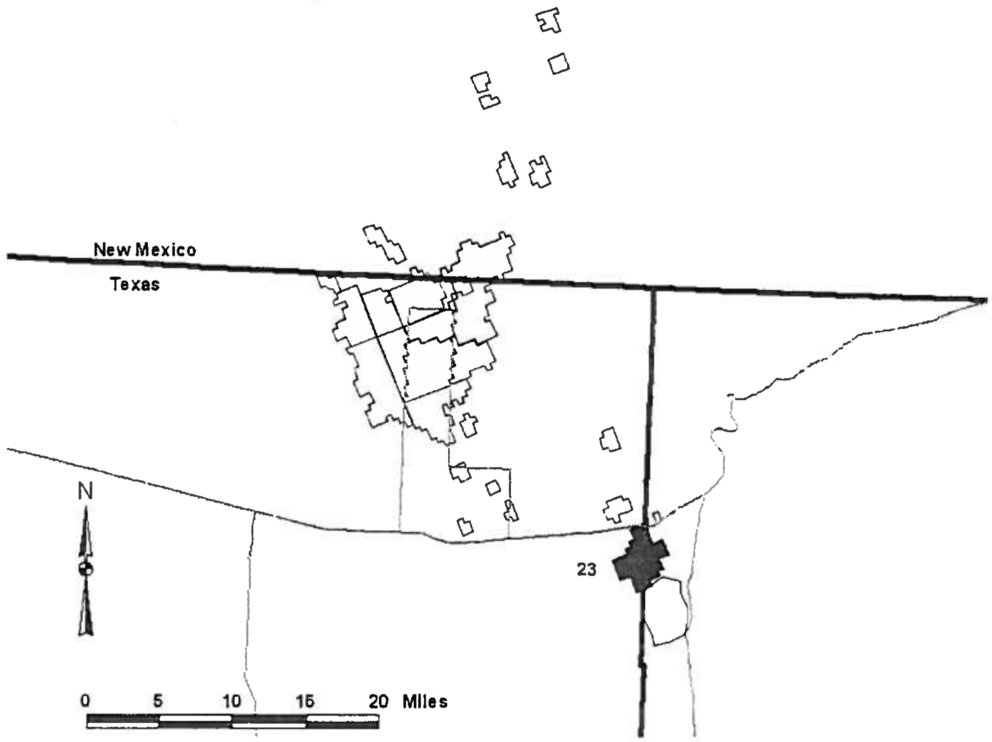
Pumping Zone 21



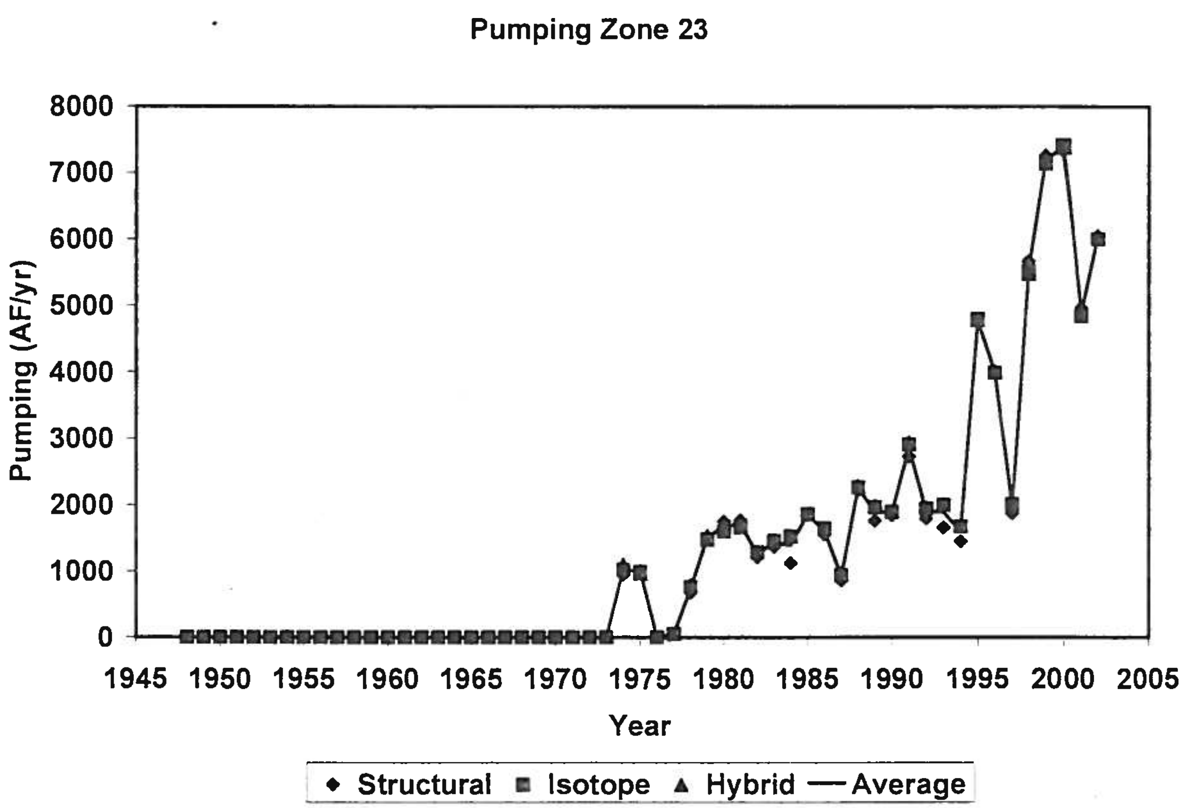


Pumping Zone 22

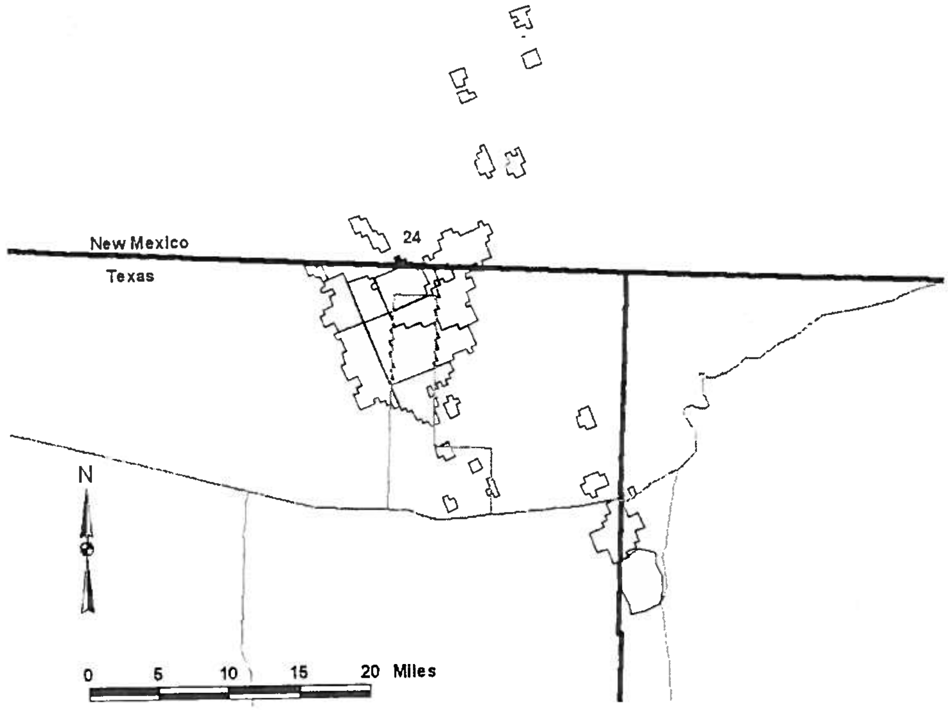




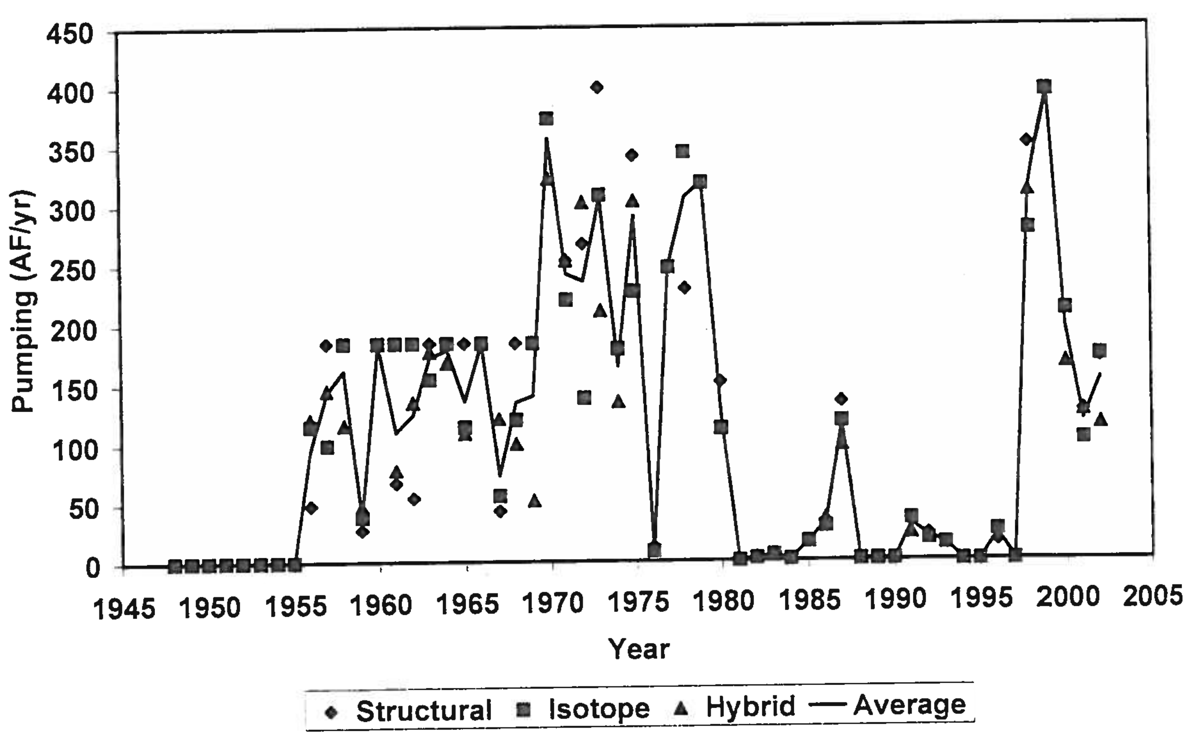
New Mexico
Texas
N
23
0 5 10 15 20 Miles

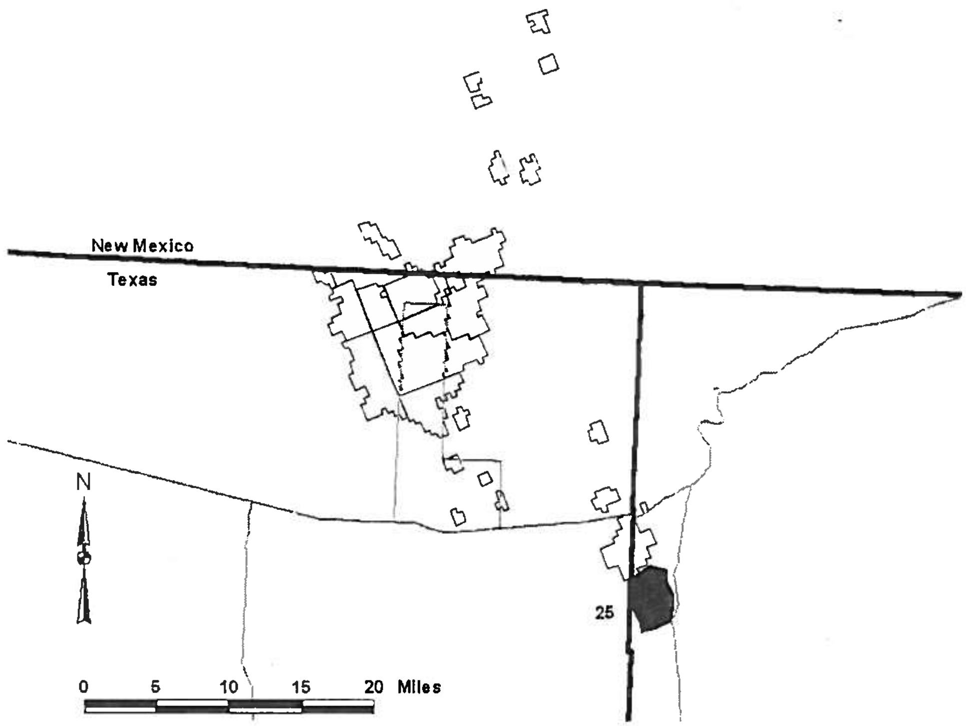


Pumping Zone 23
8000
7000
6000
5000
4000
3000
2000
1000
0
Pumping (AF/yr)
1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005
Year
Structural
Isotope
Hybrid
Average

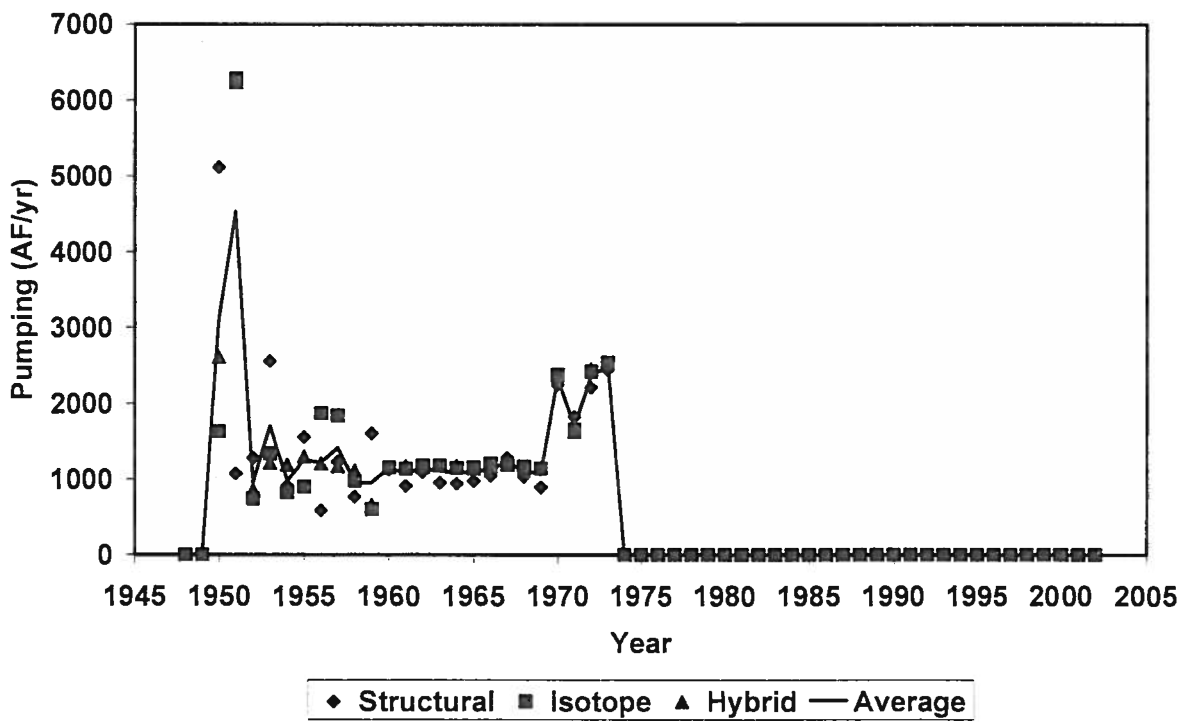


Pumping Zone 24



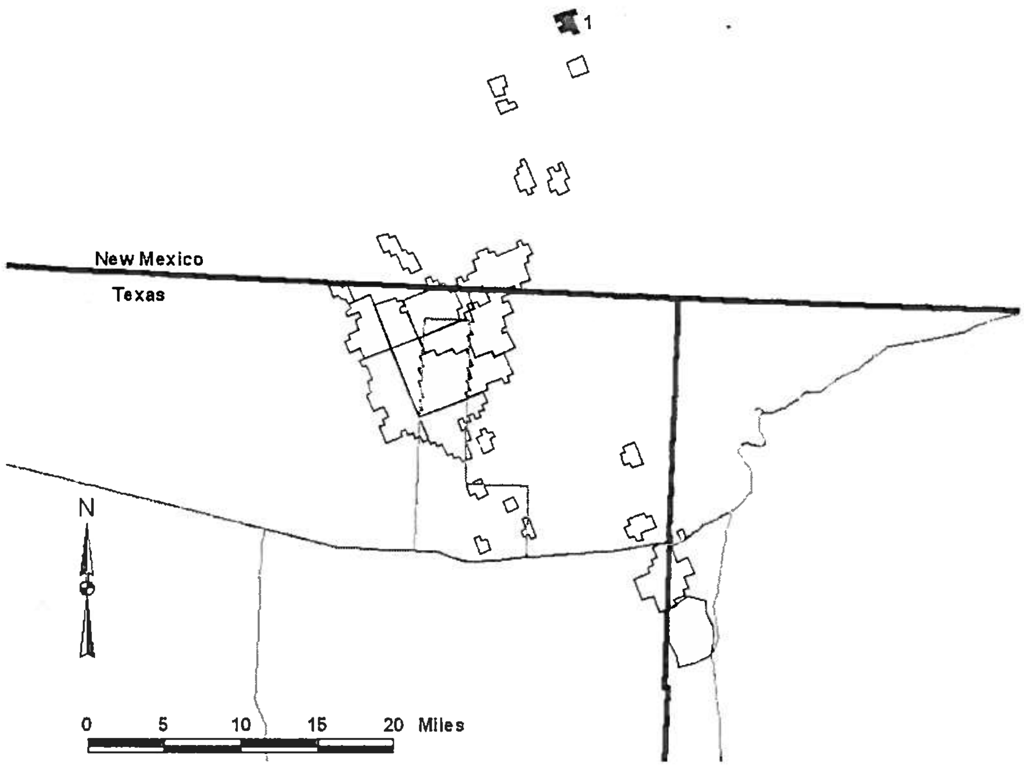


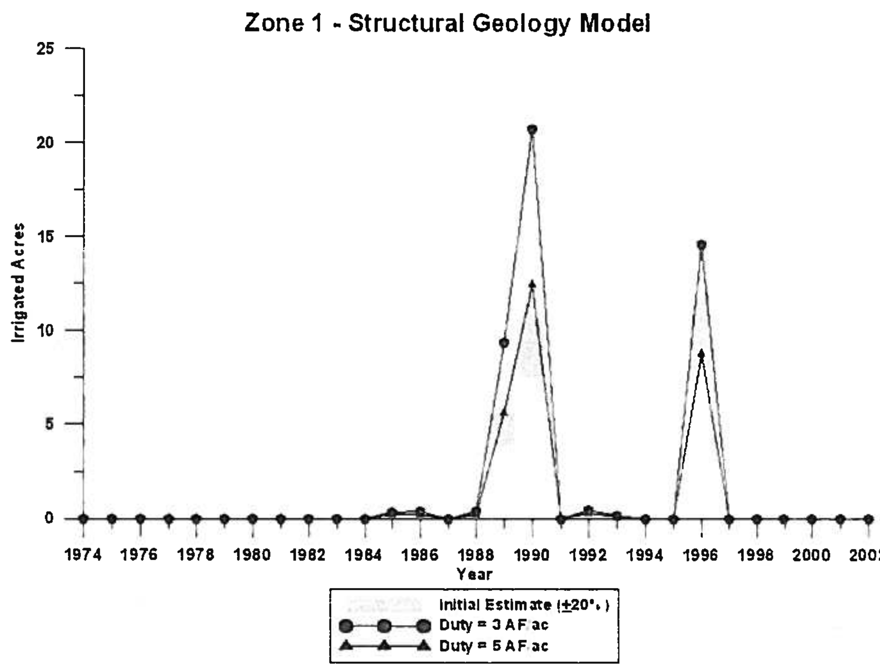
Pumping Zone 25



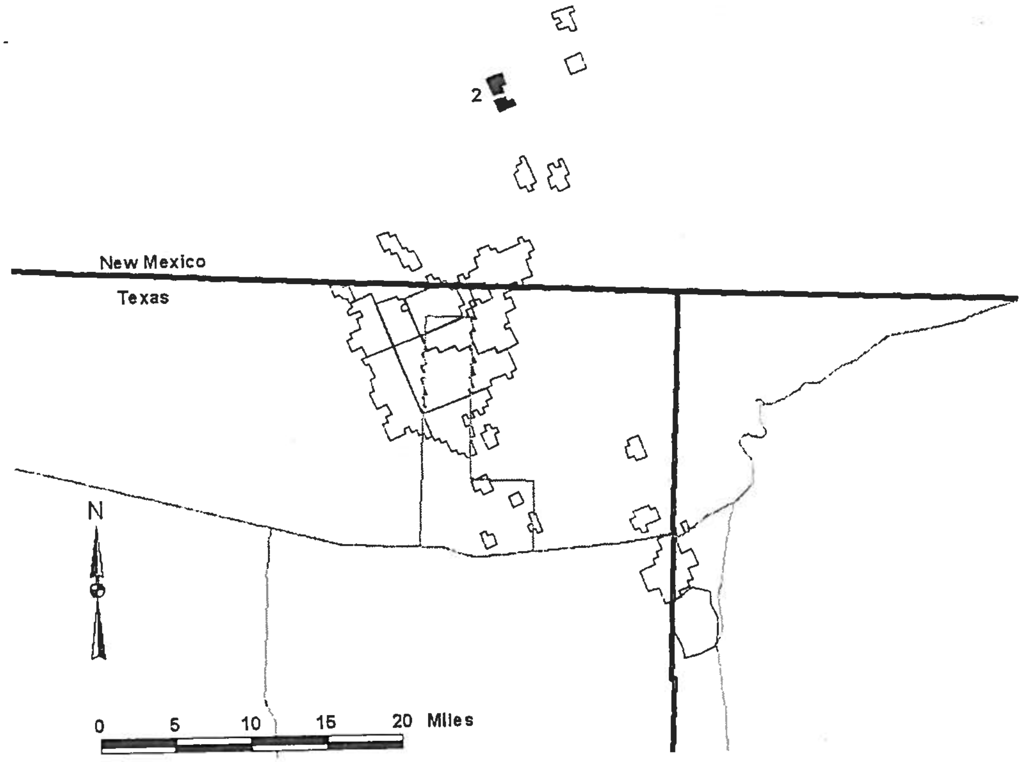
Appendix B-1

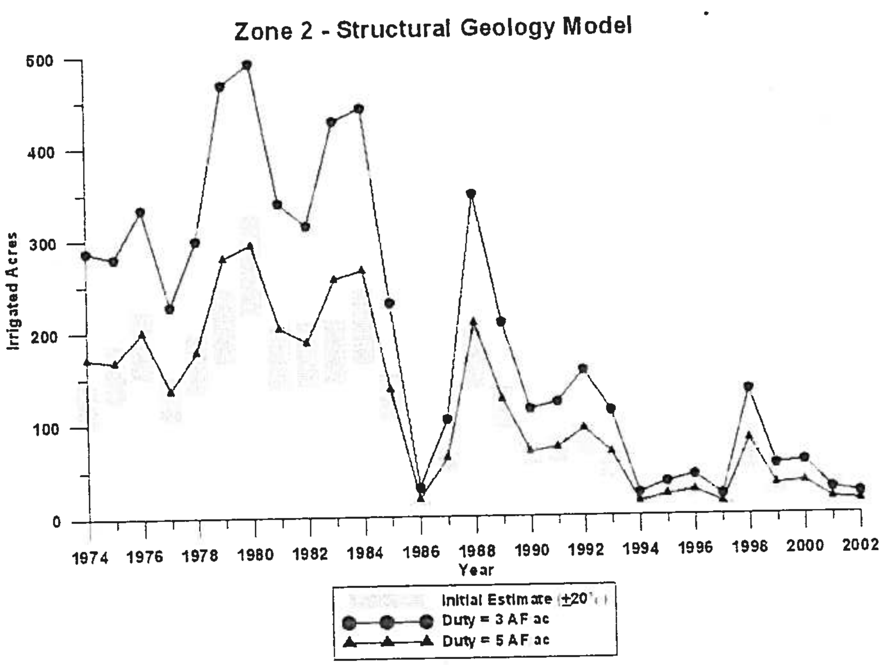
Irrigated Acreage Estimates for Each Pumping Zone
Structural Geology Model



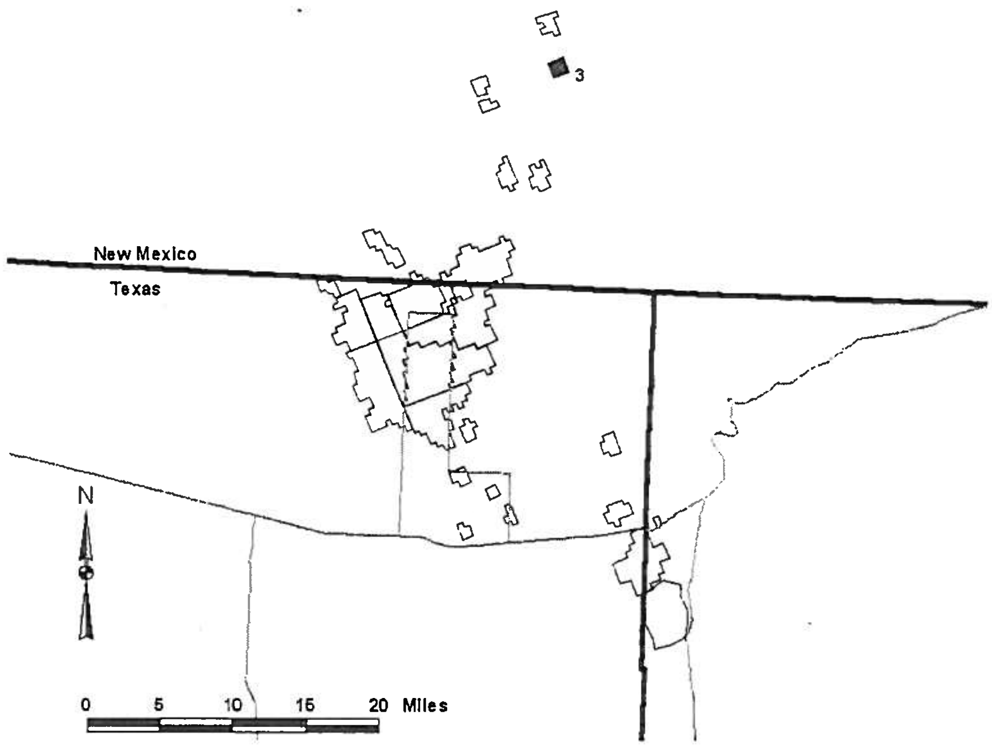


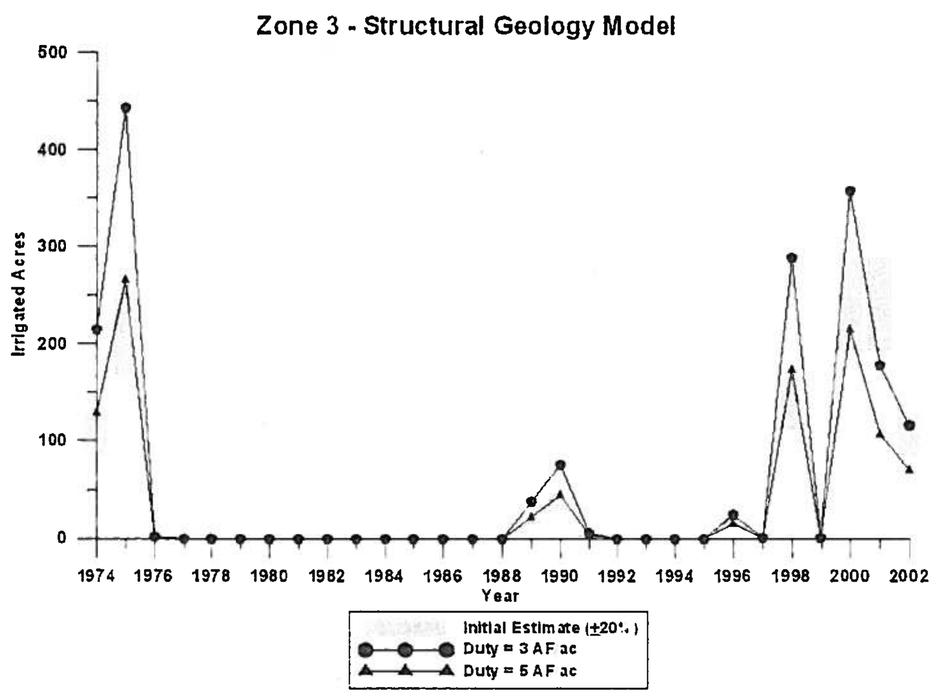
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



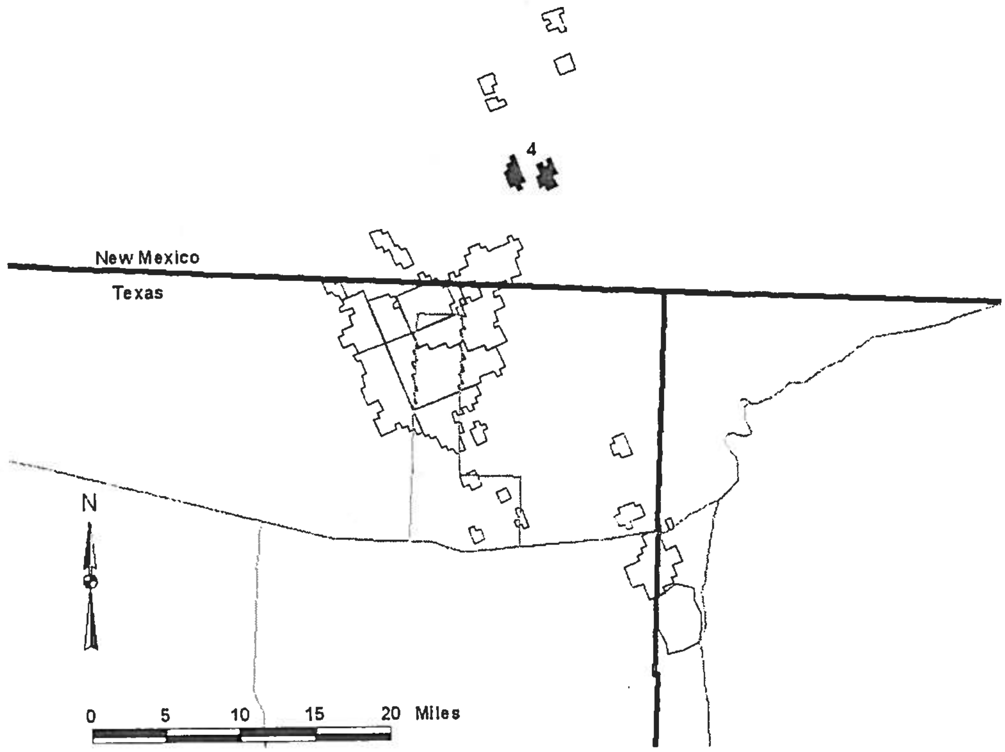


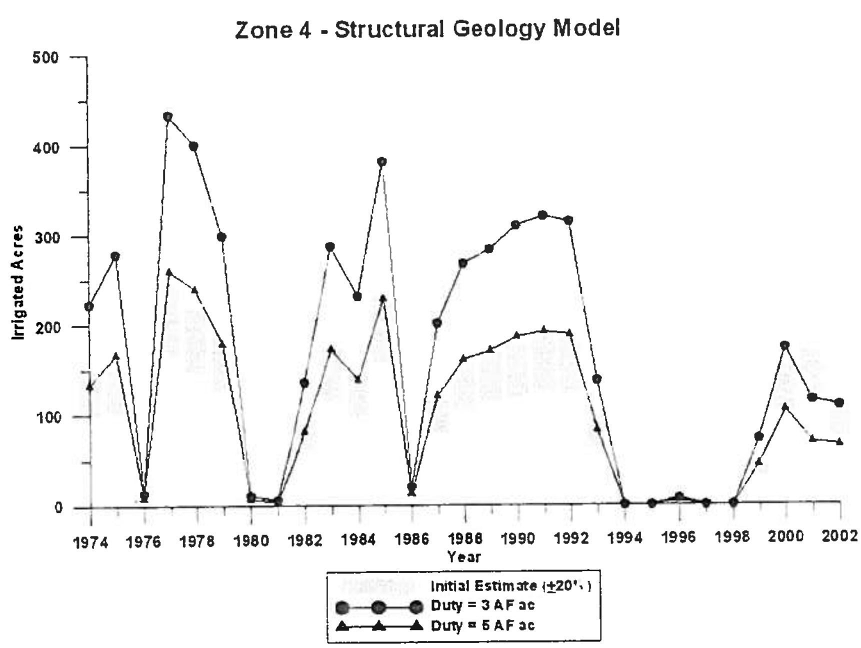
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



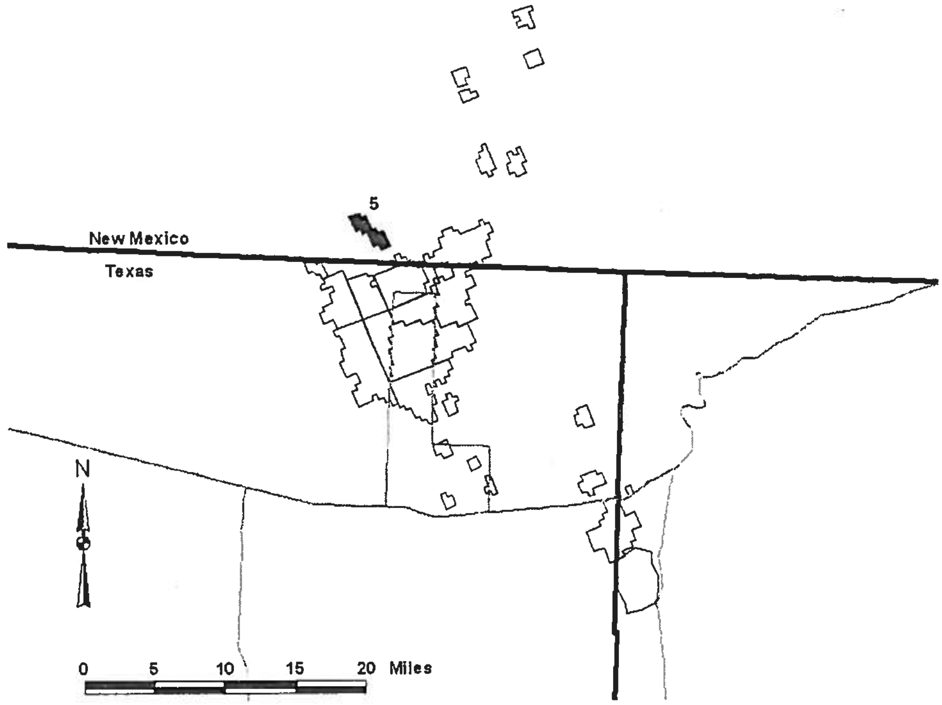


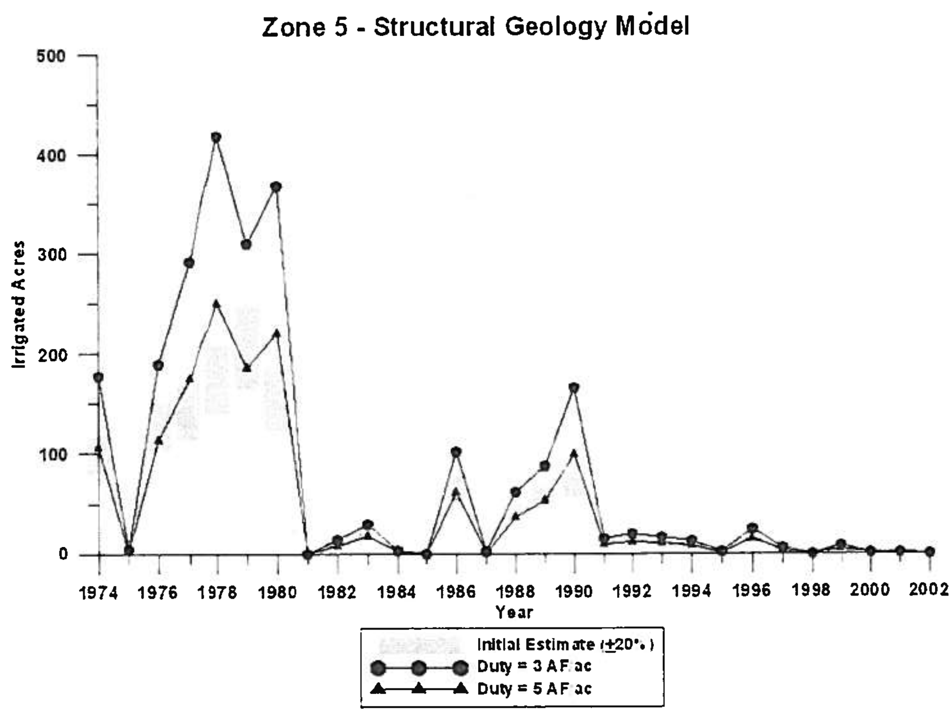
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



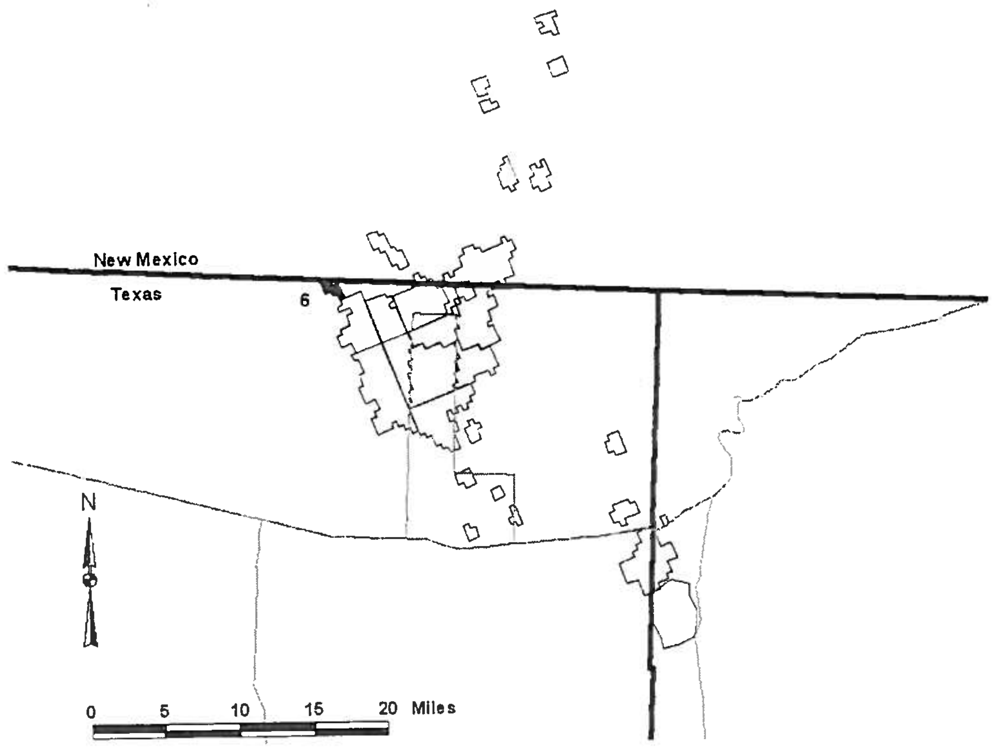


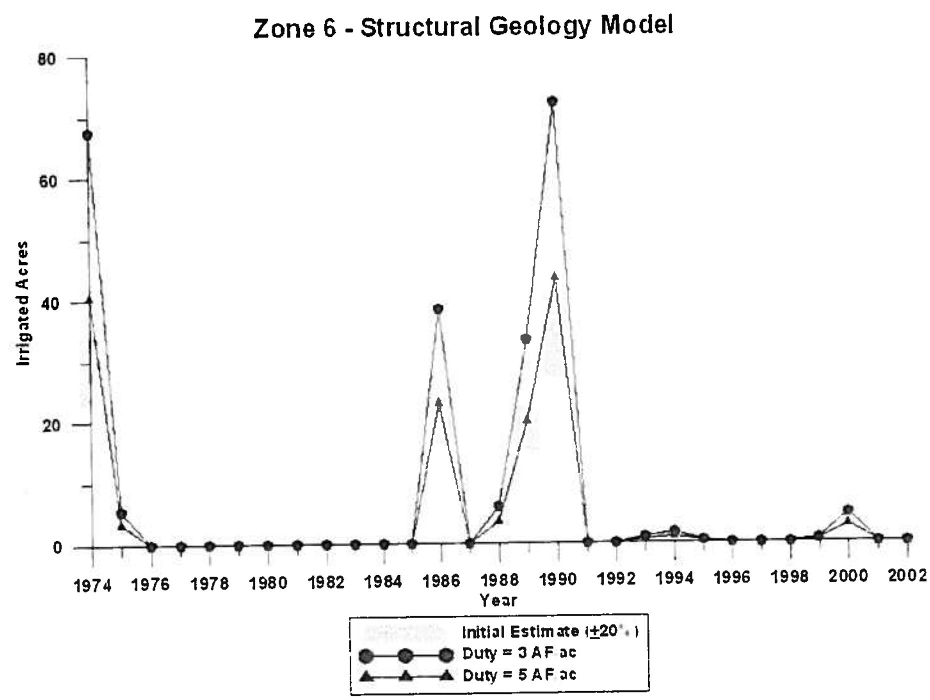
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



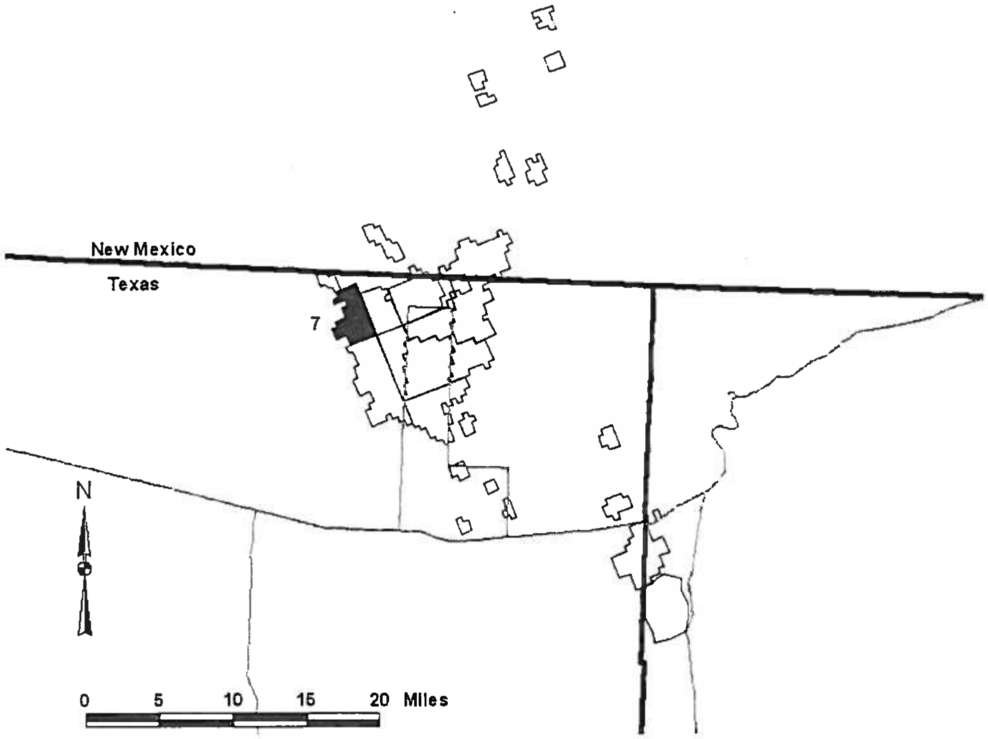


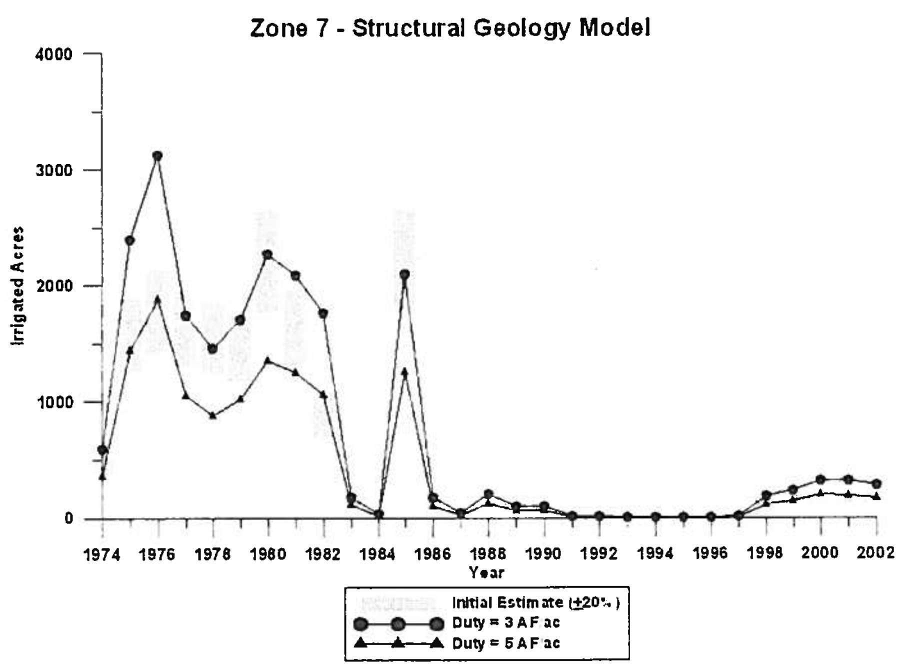
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



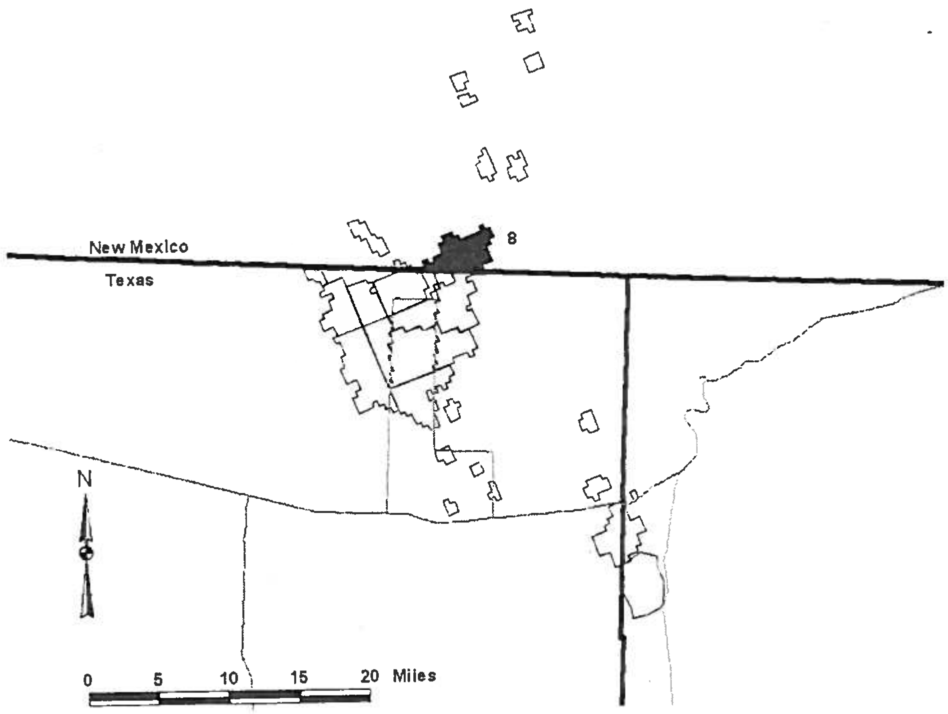


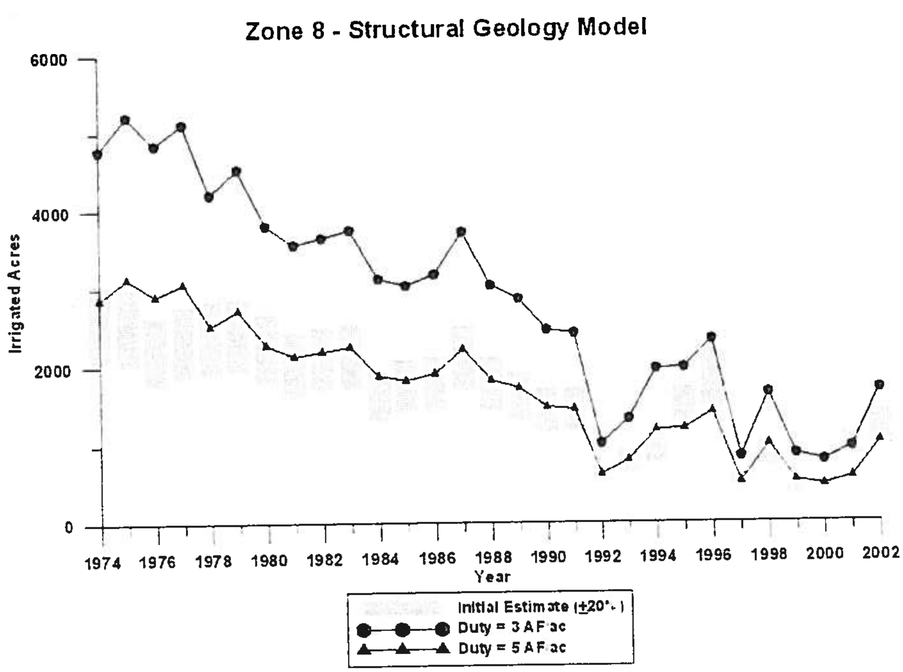
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



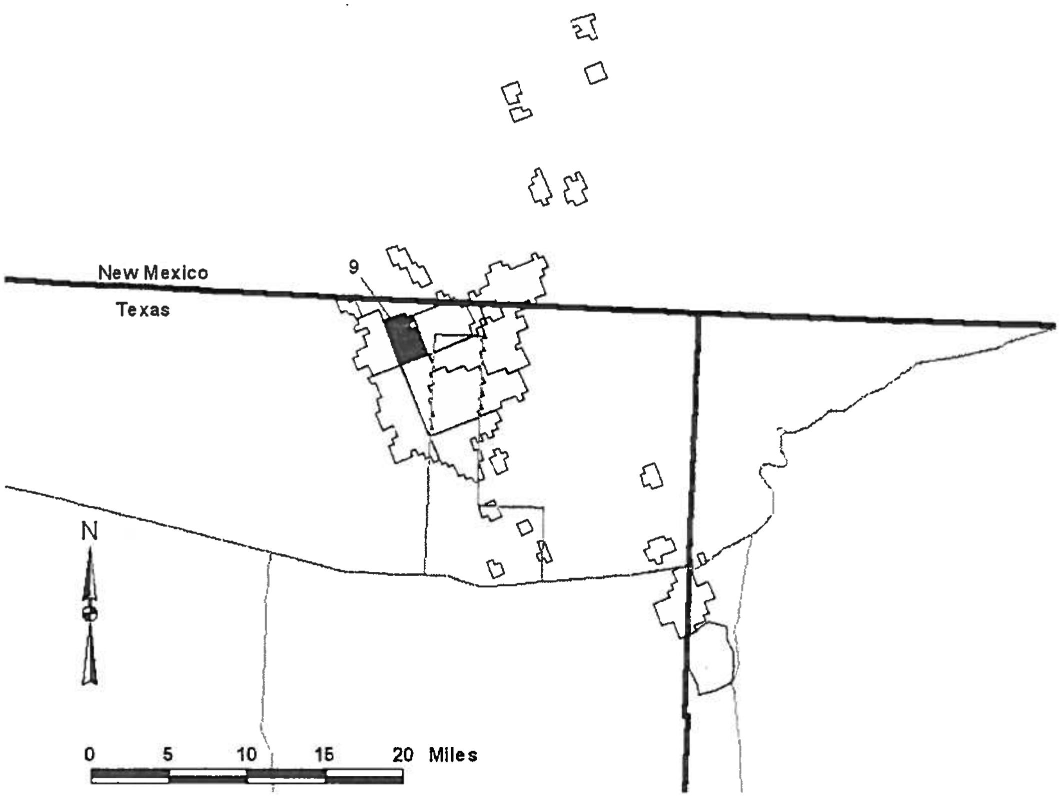


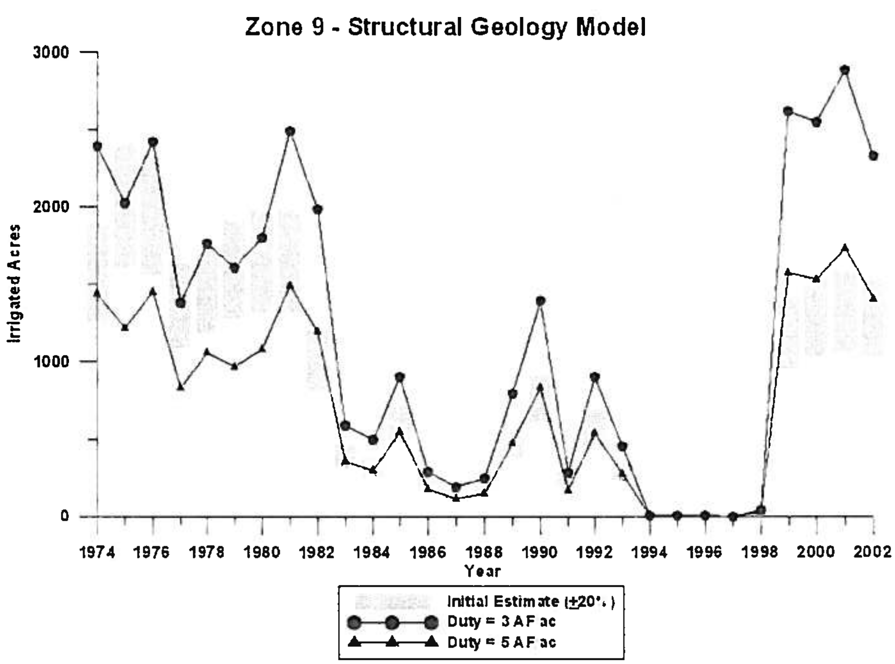
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



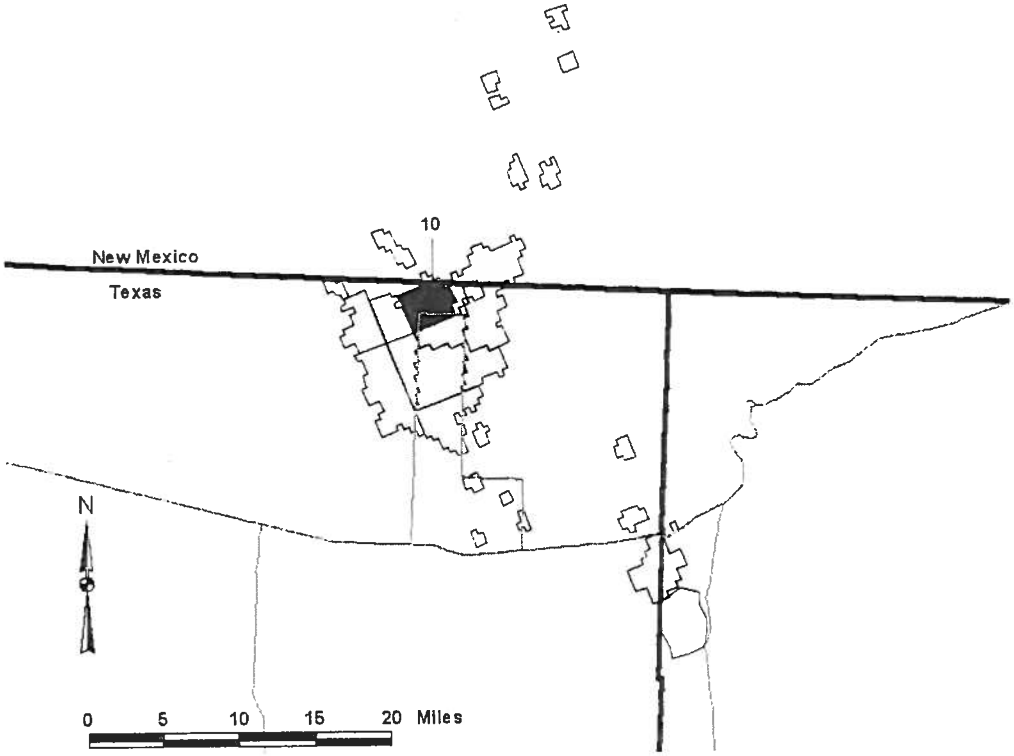


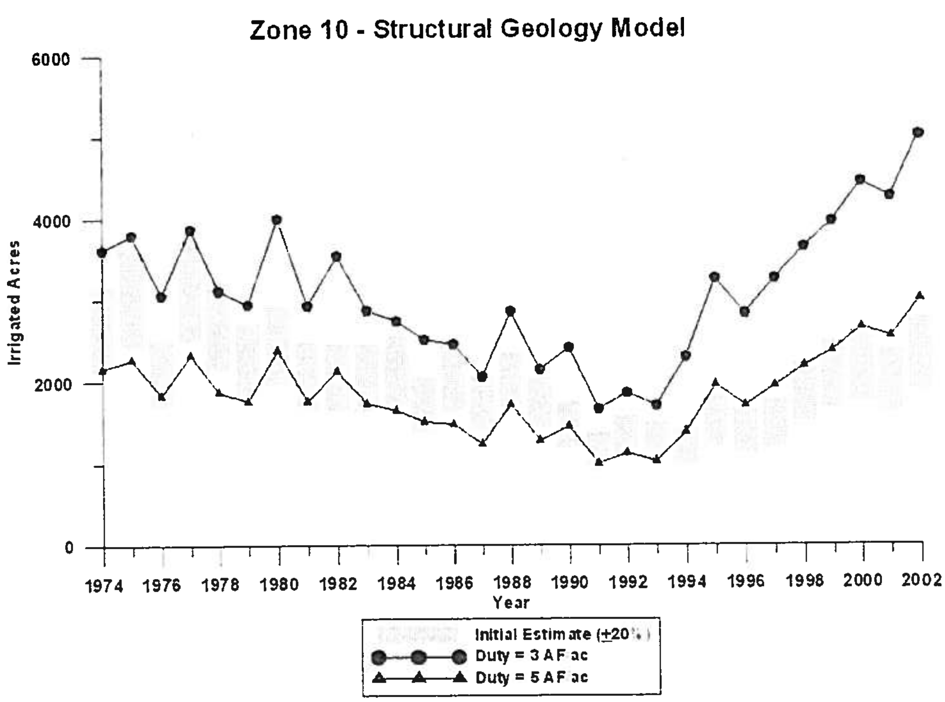
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



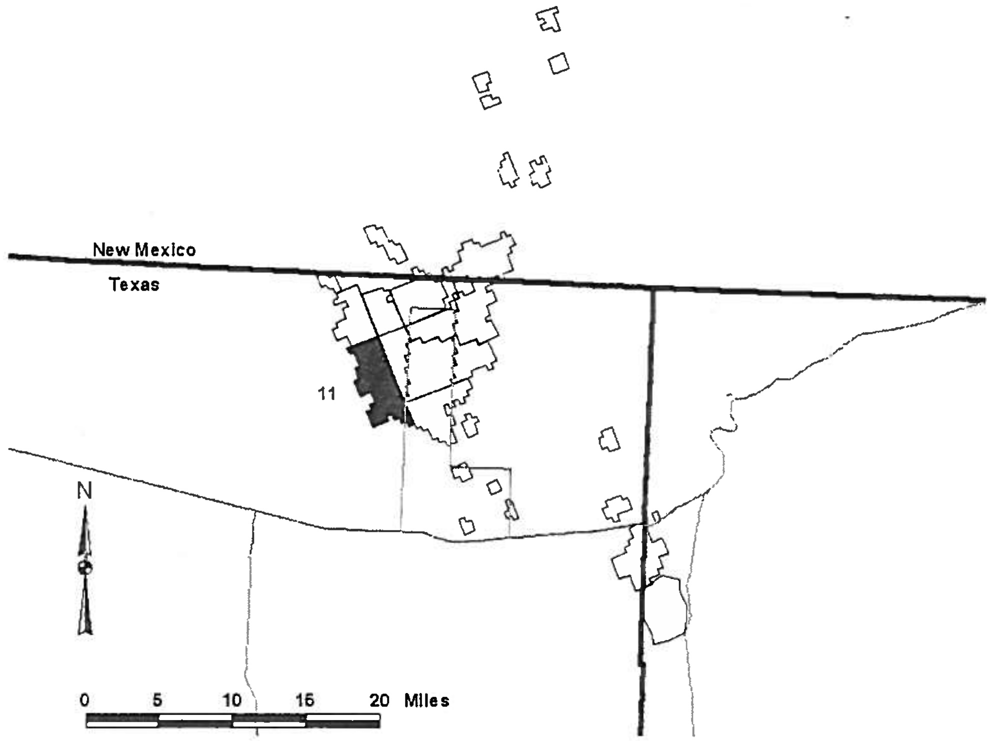


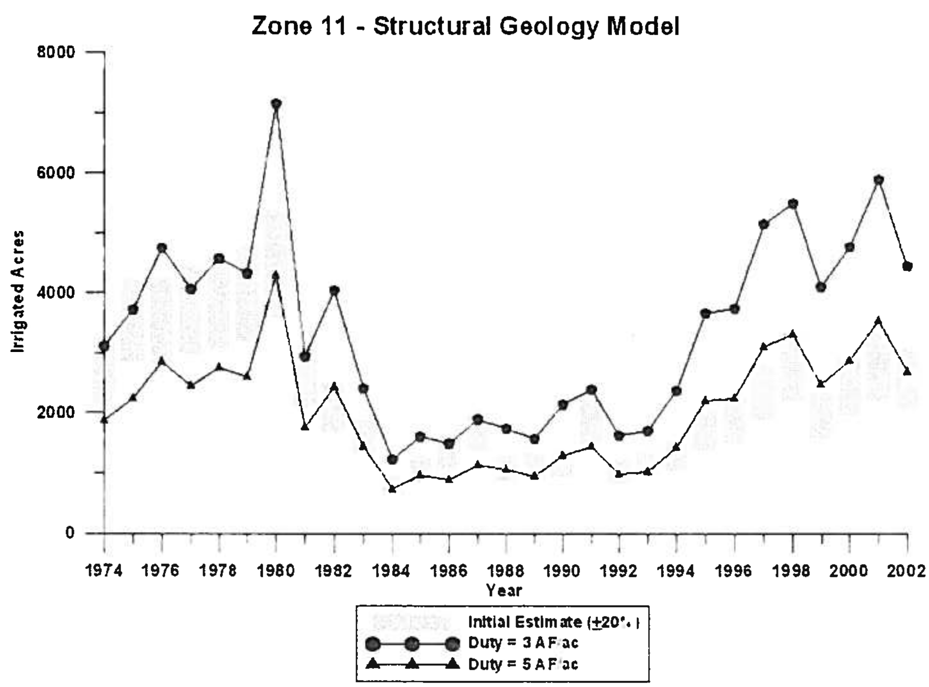
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



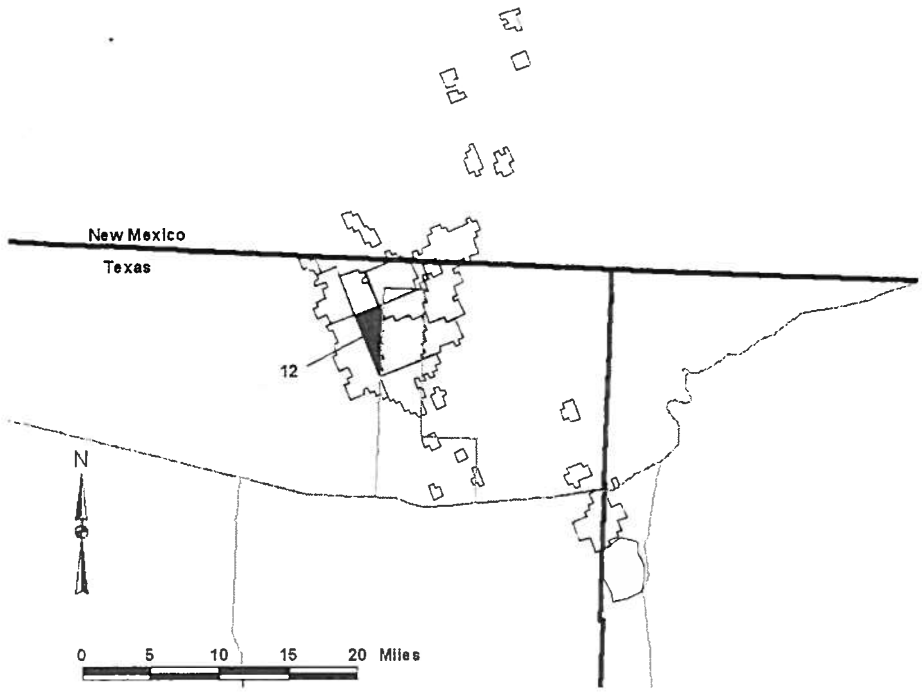


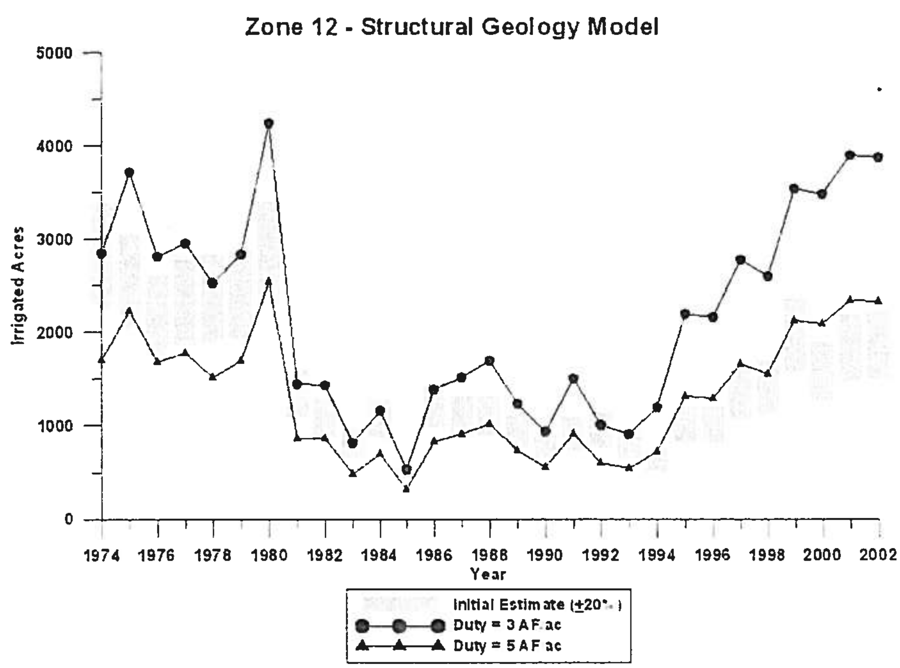
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



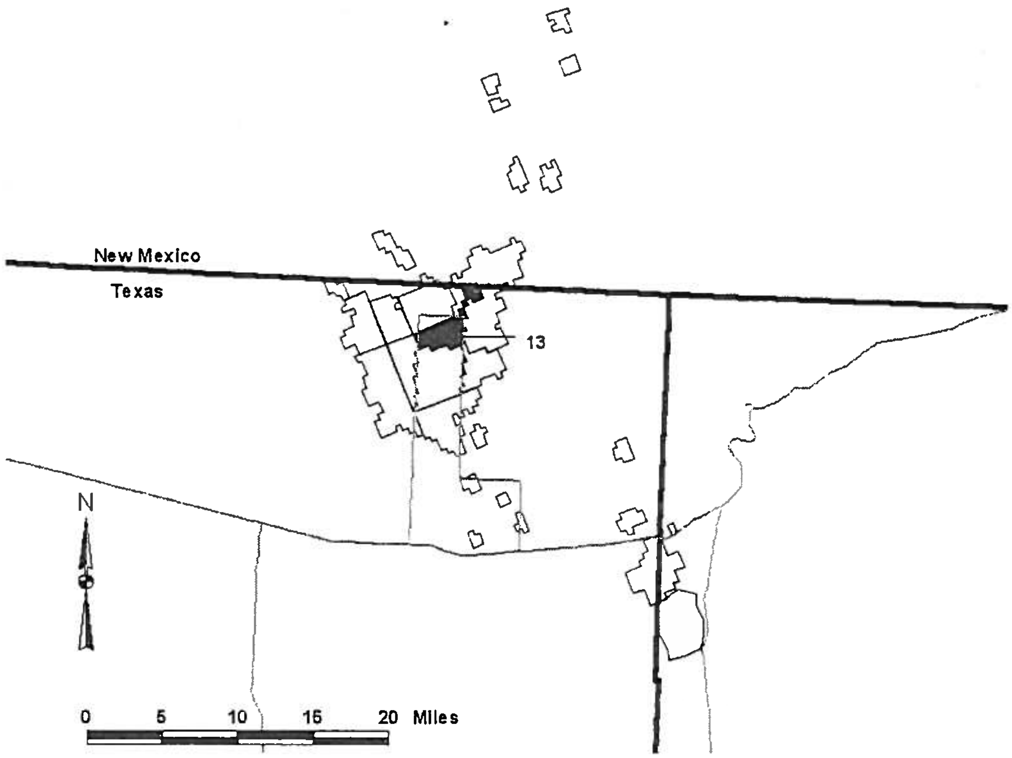


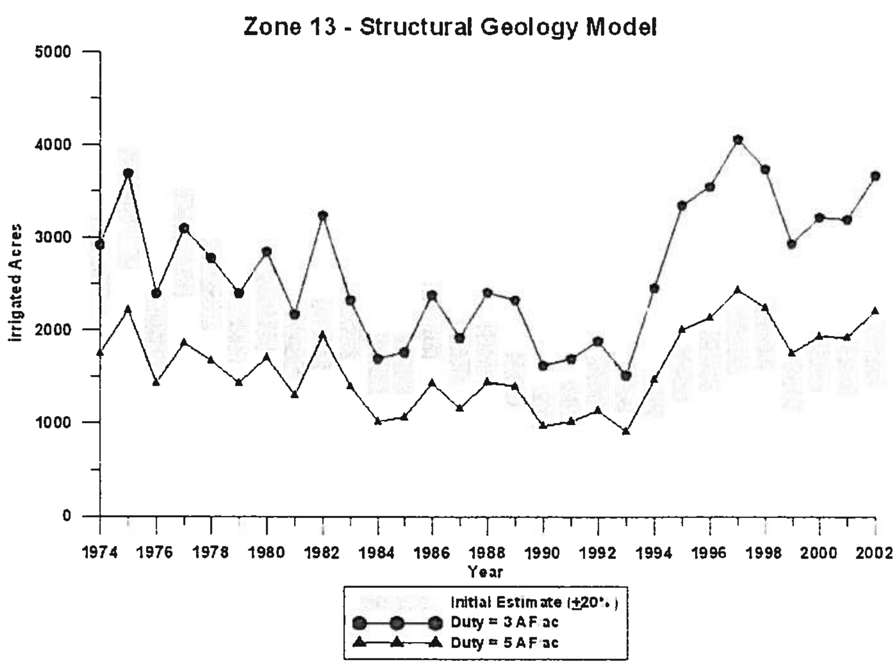
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



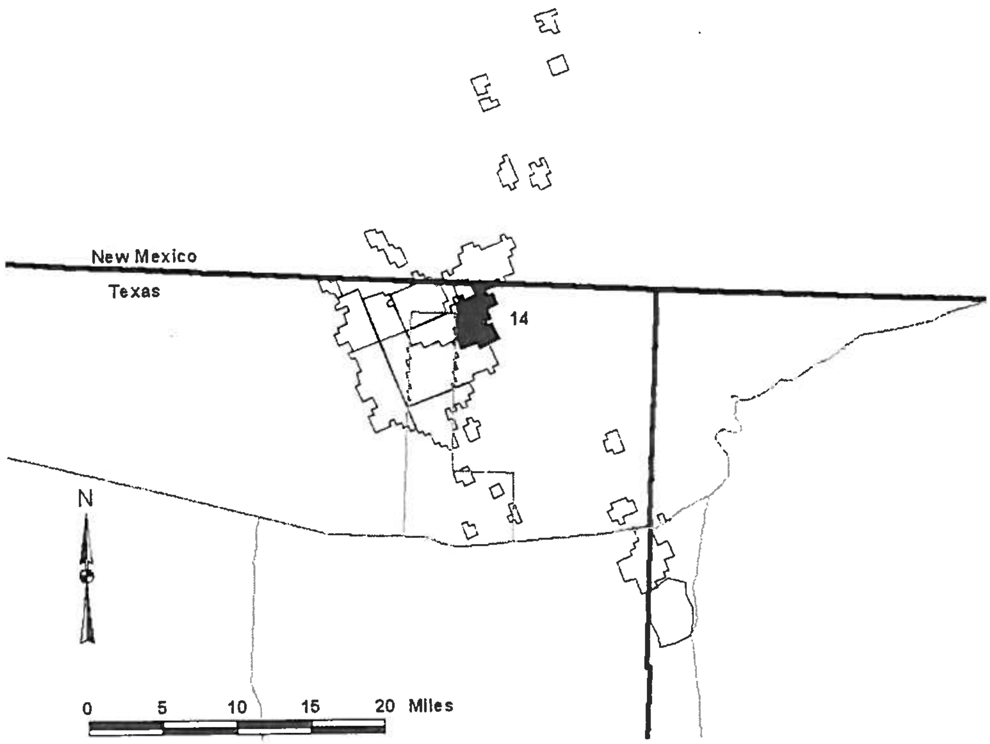


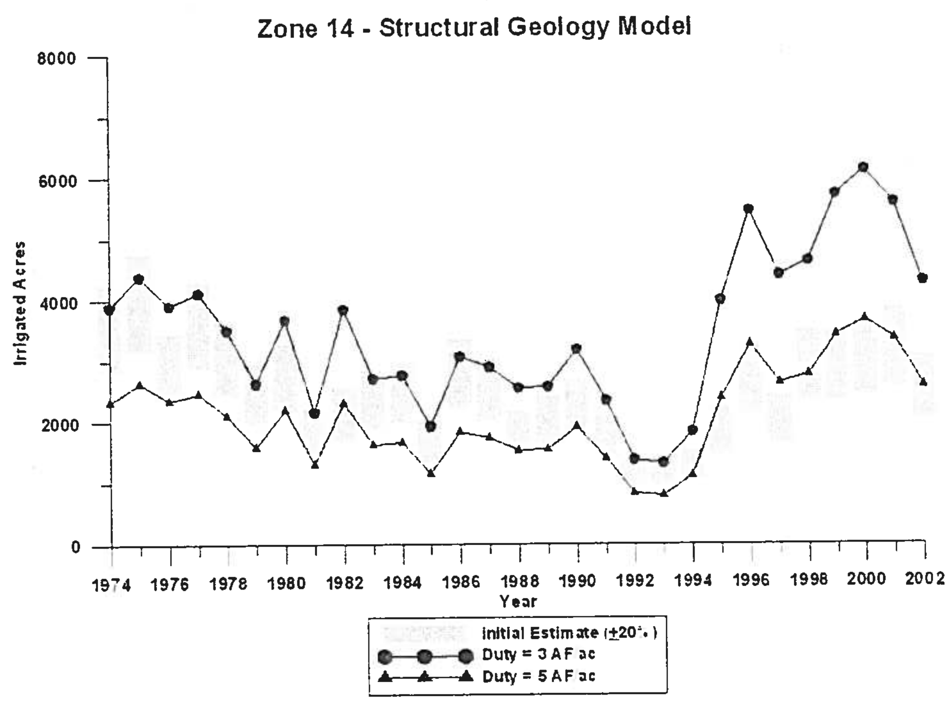
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



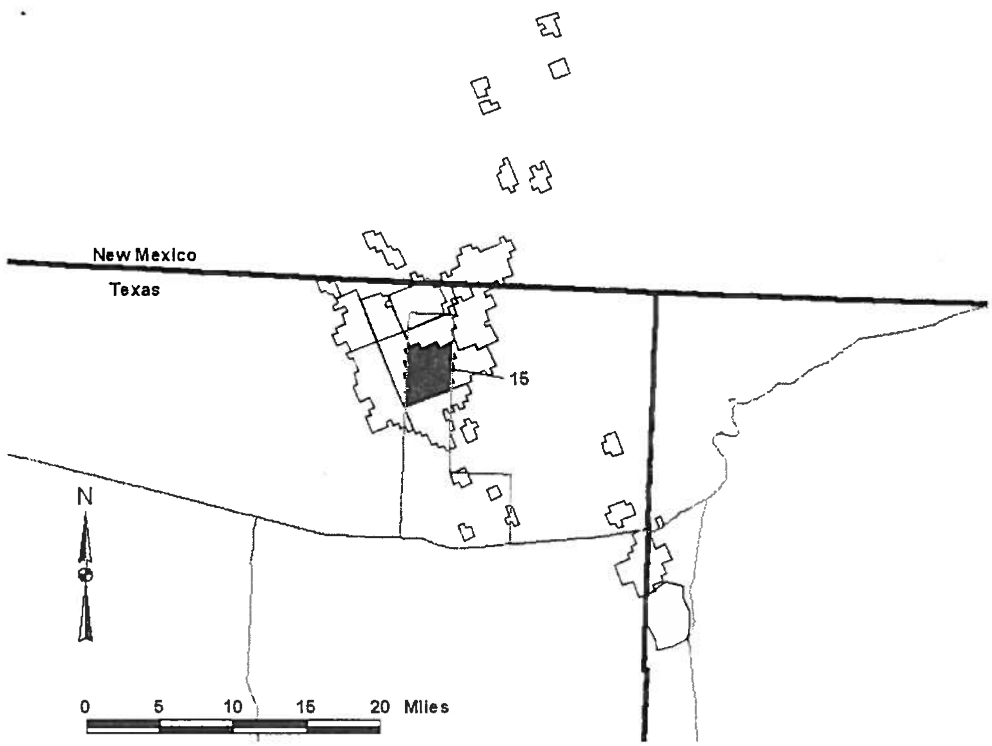


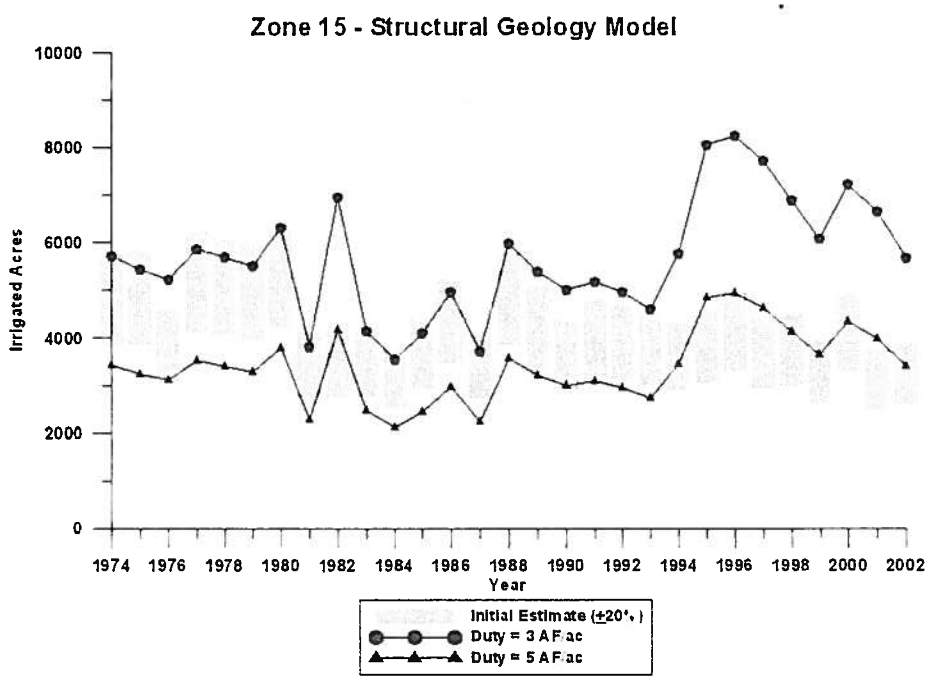
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



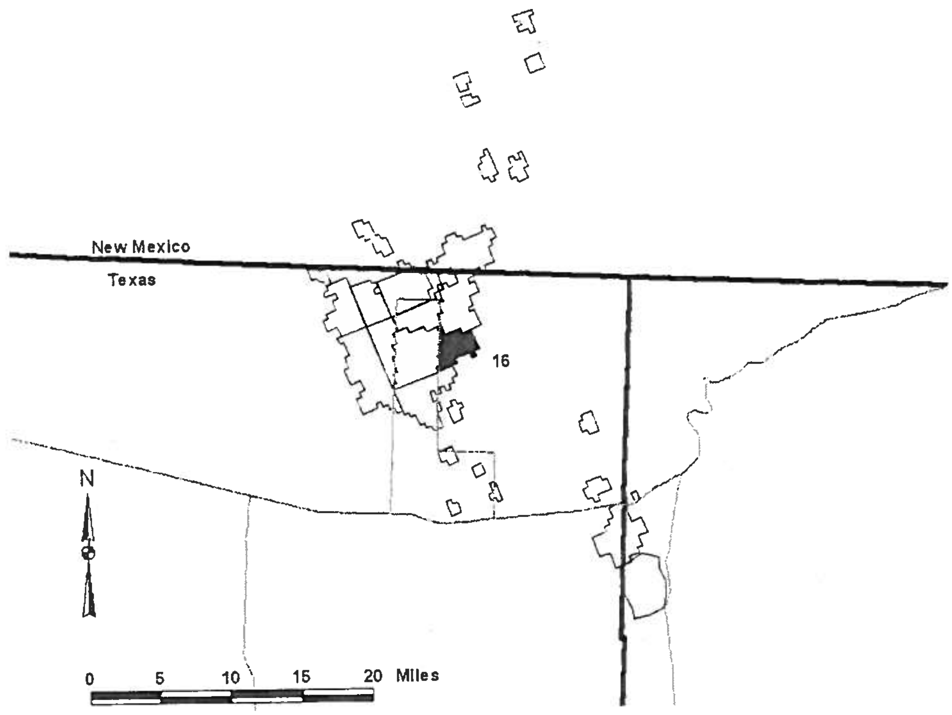


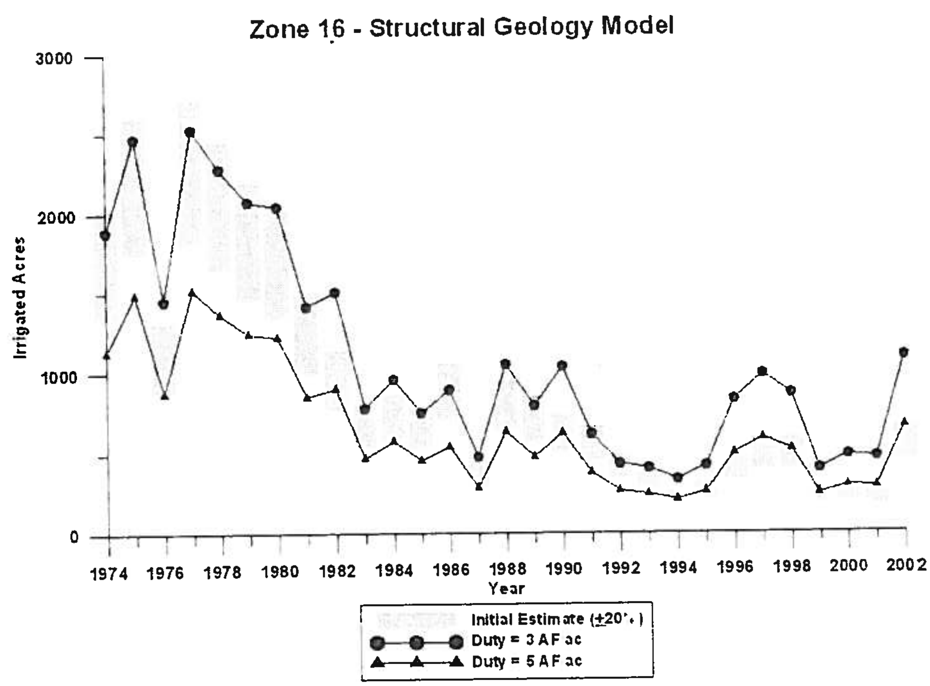
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



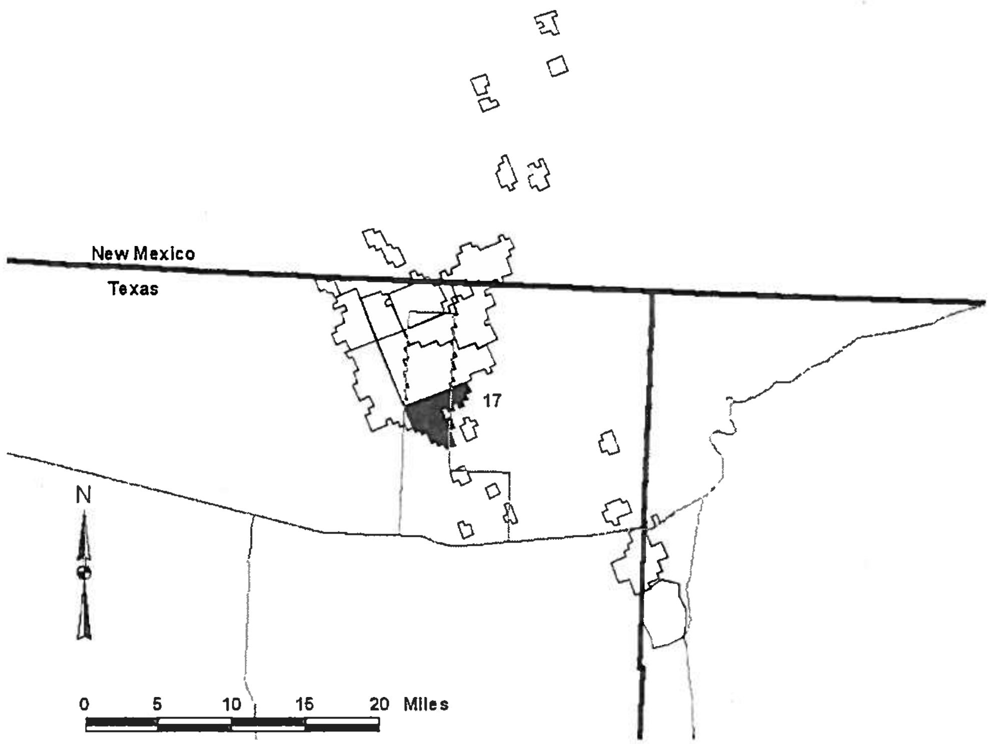


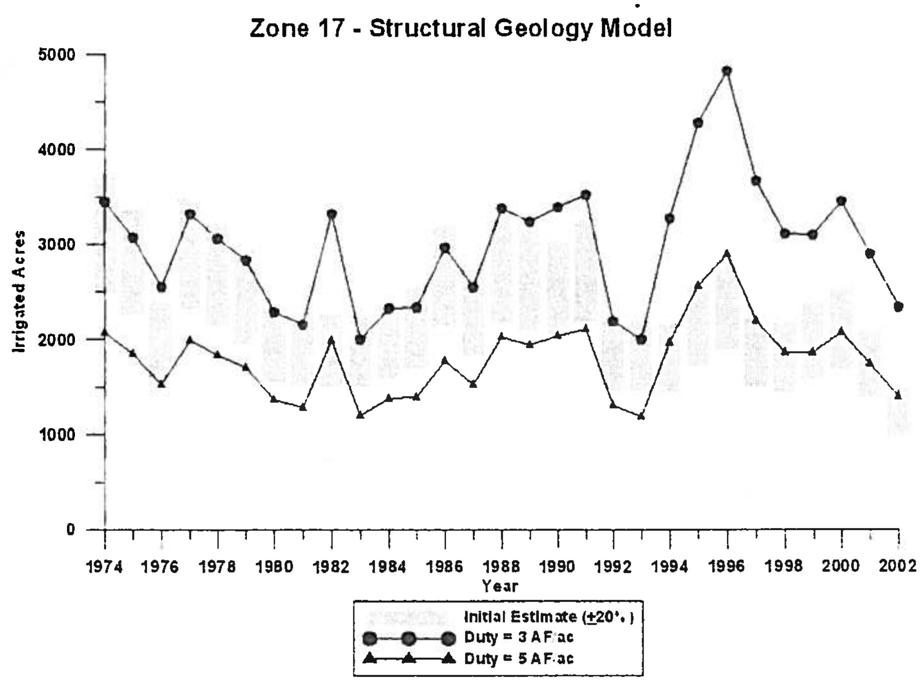
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



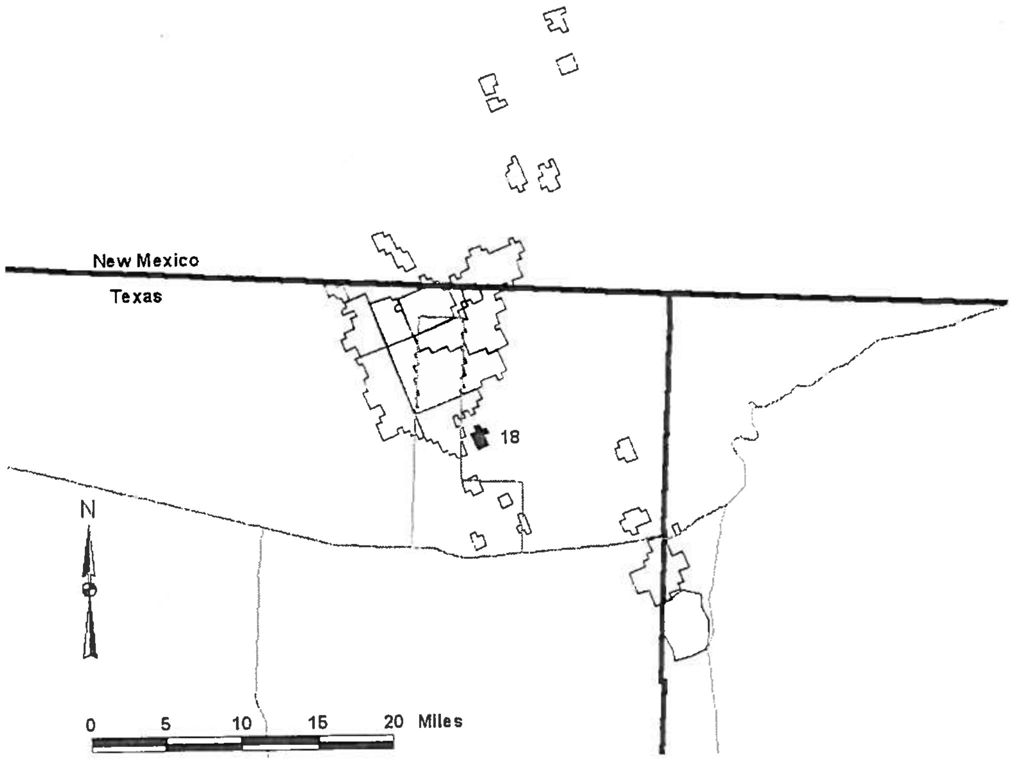


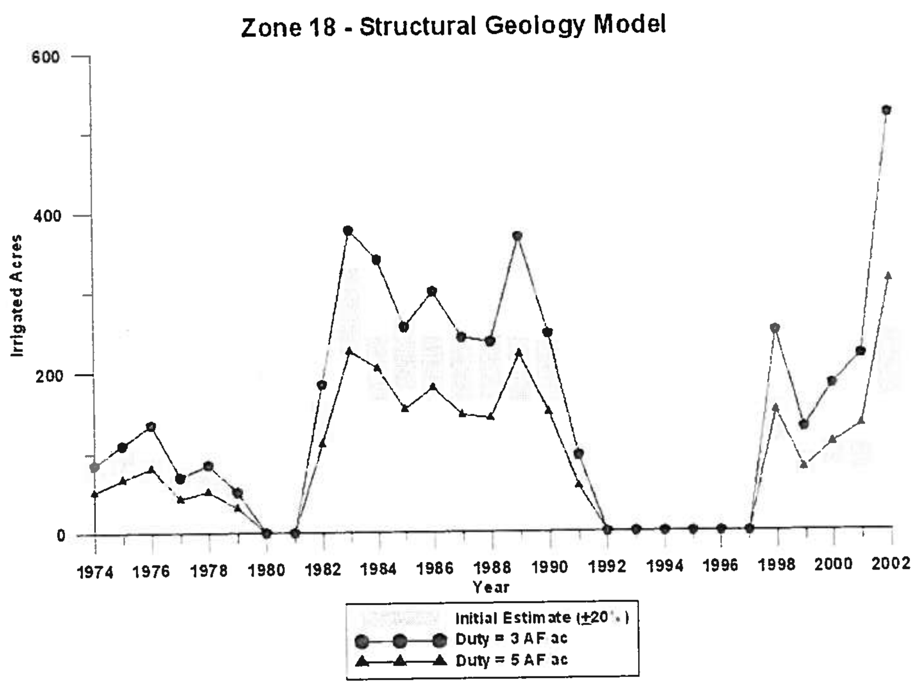
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



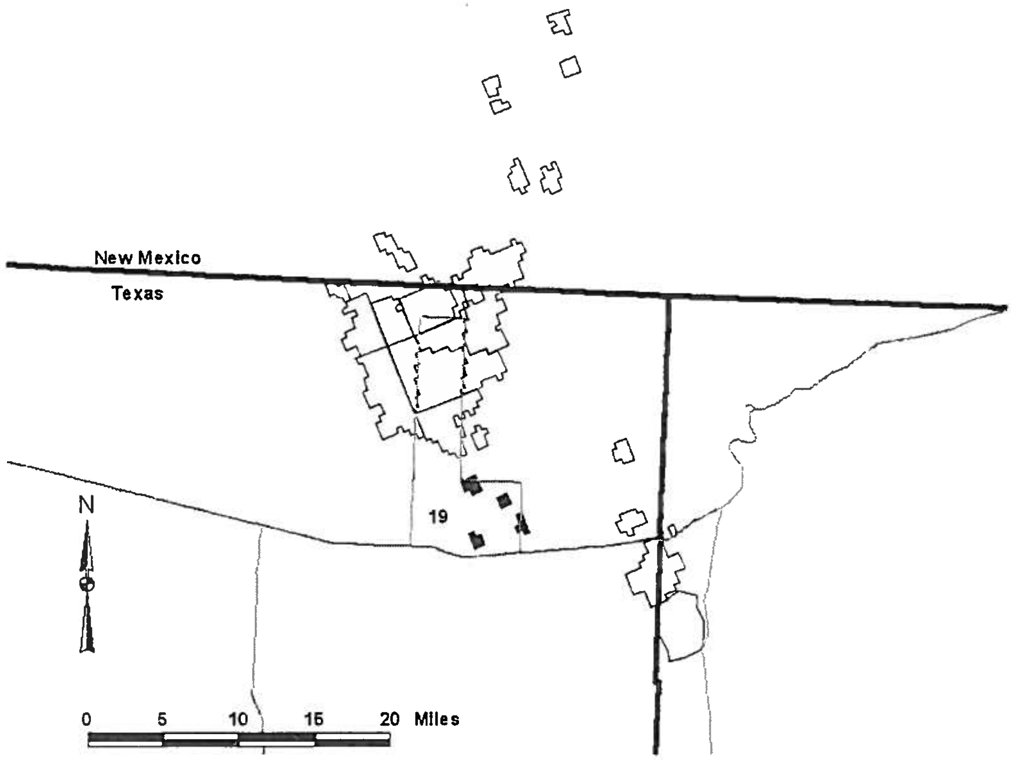


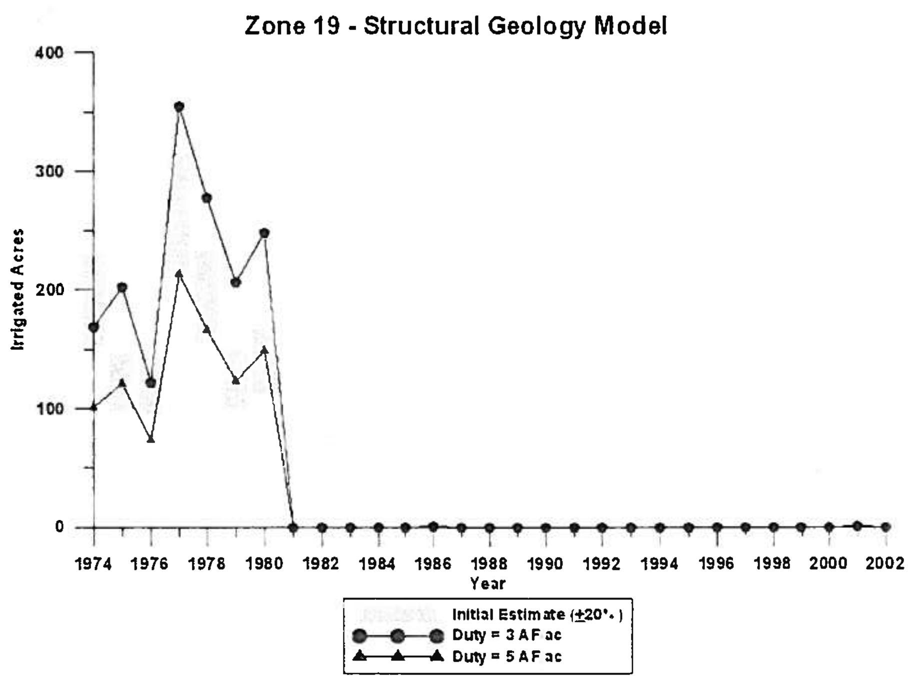
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



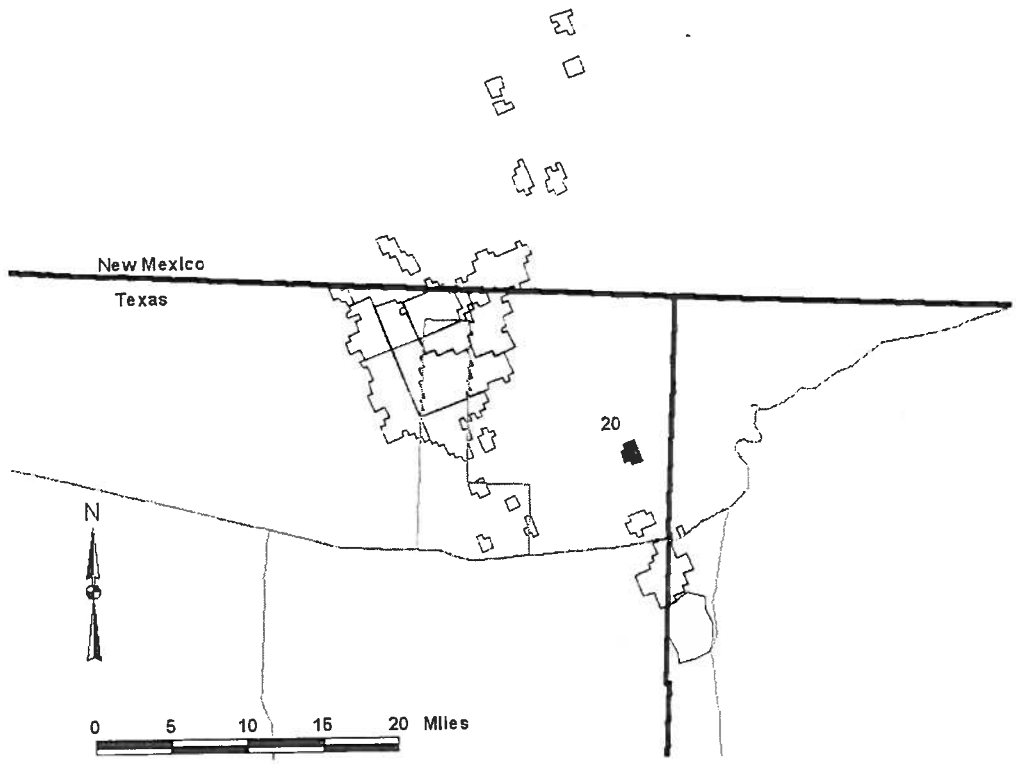


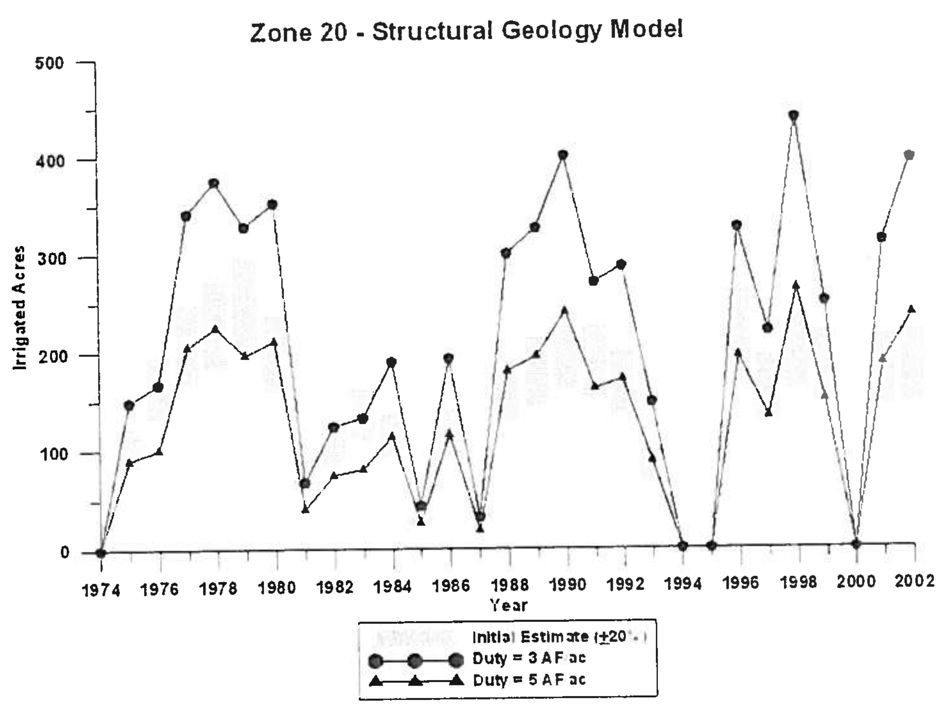
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



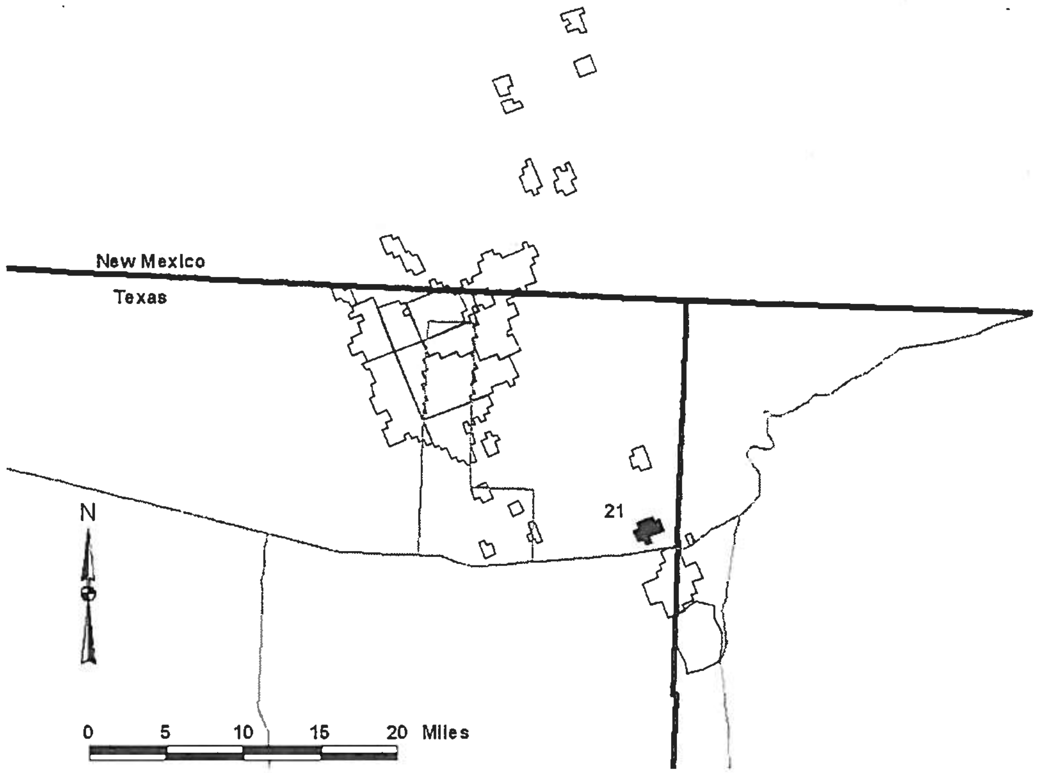


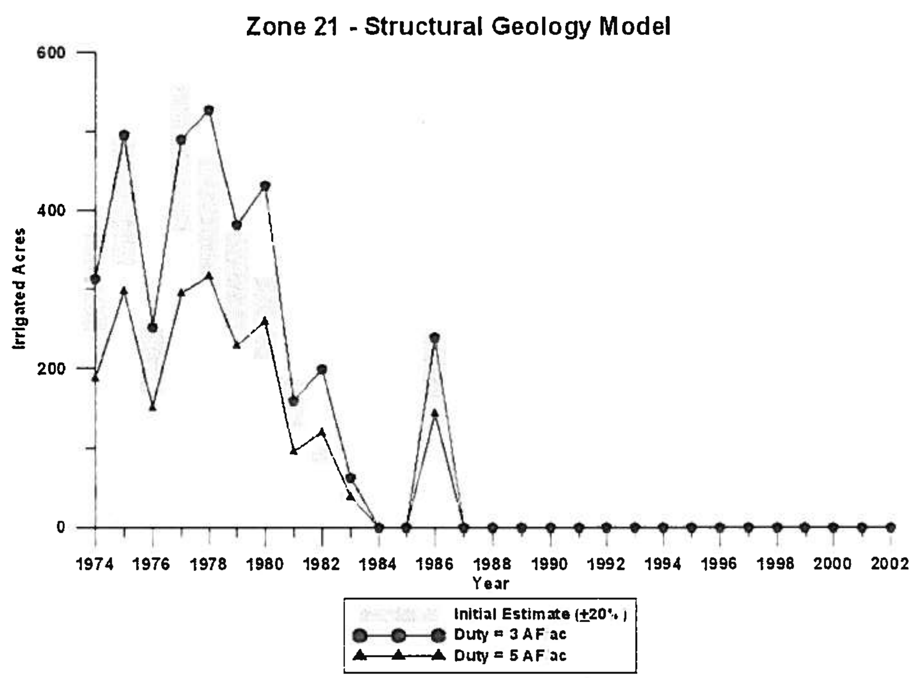
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



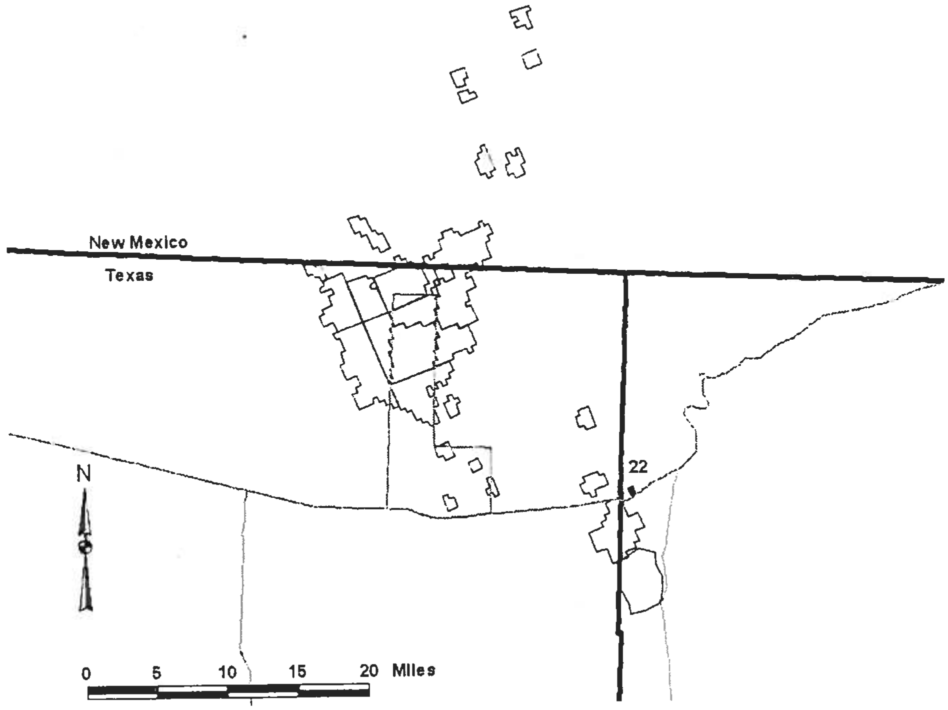


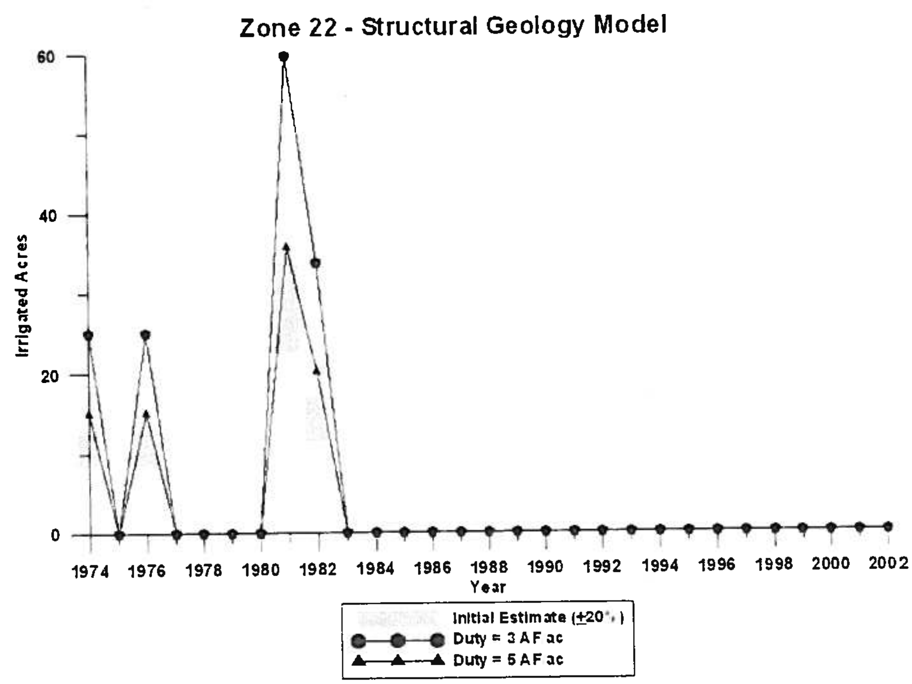
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



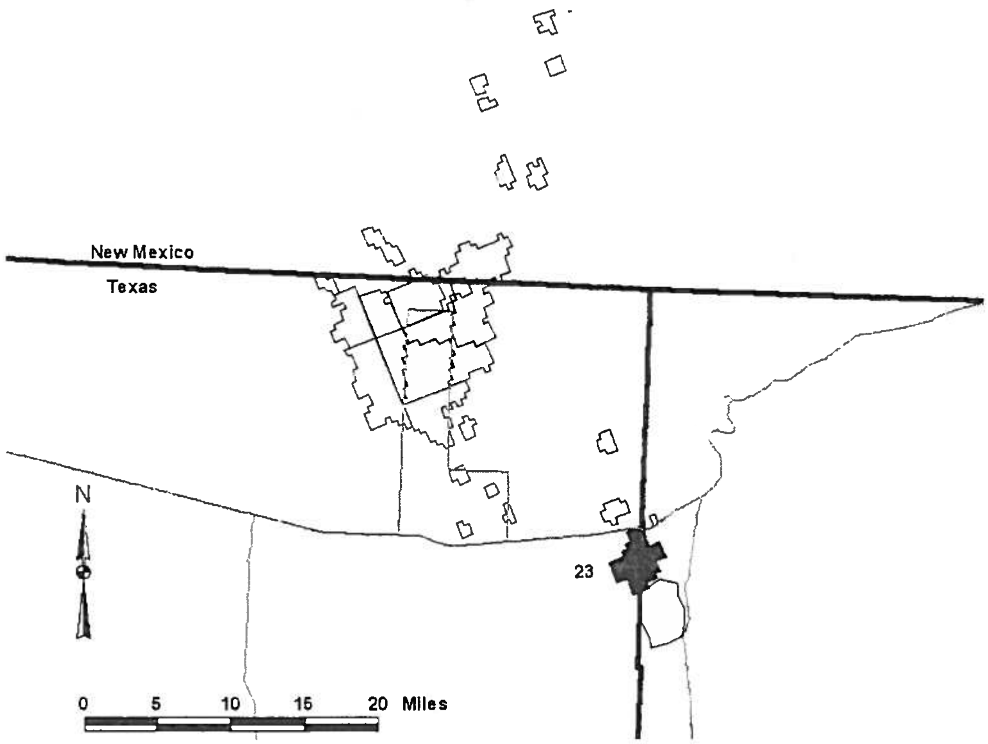


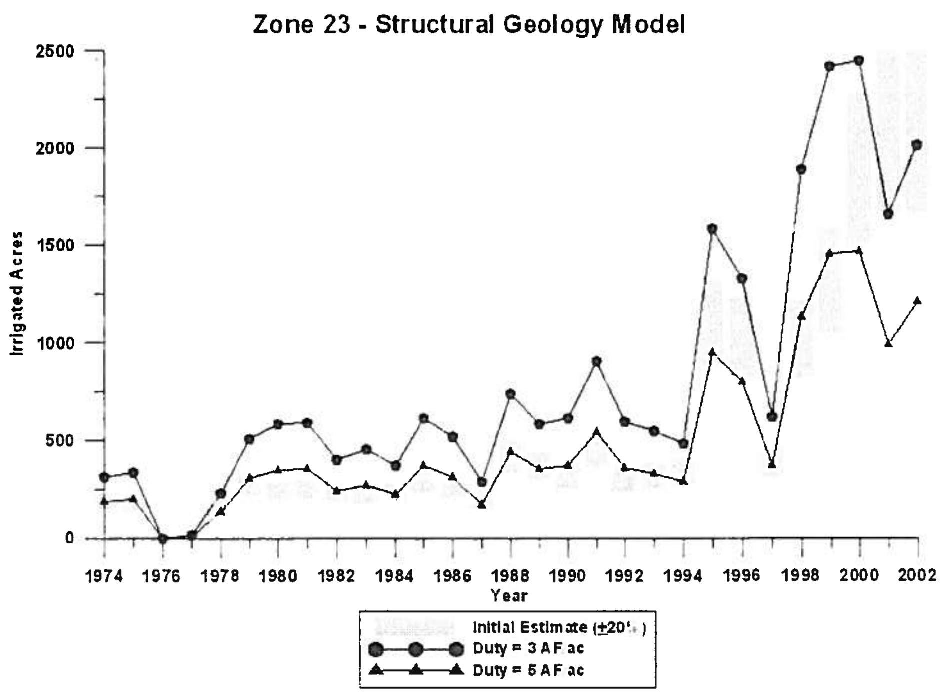
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



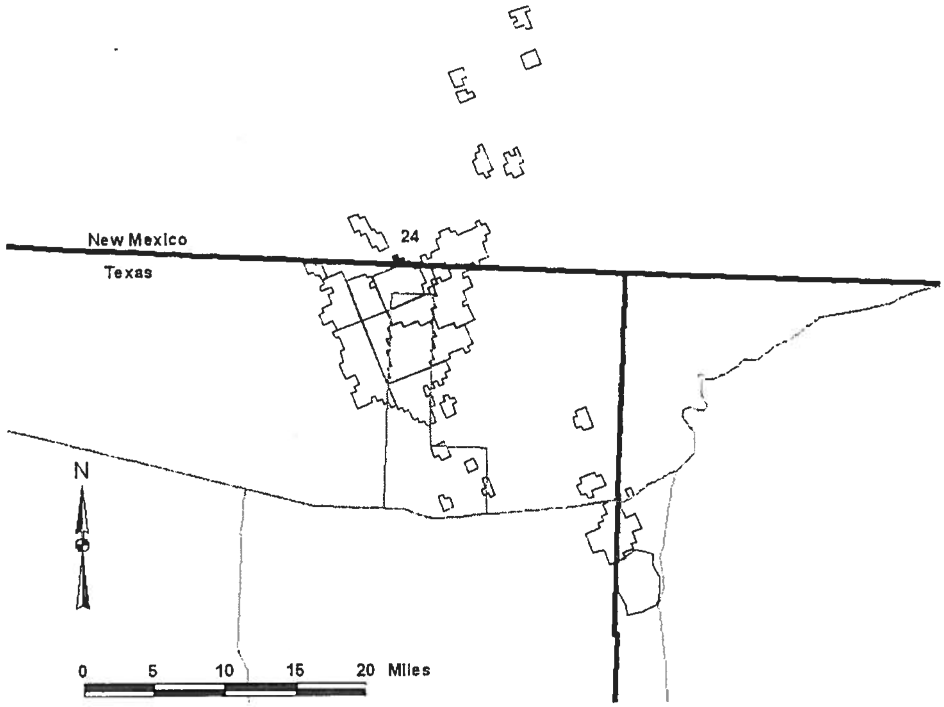


Note: Initial Estimate Range from Groeneveld and Baugh (2002)

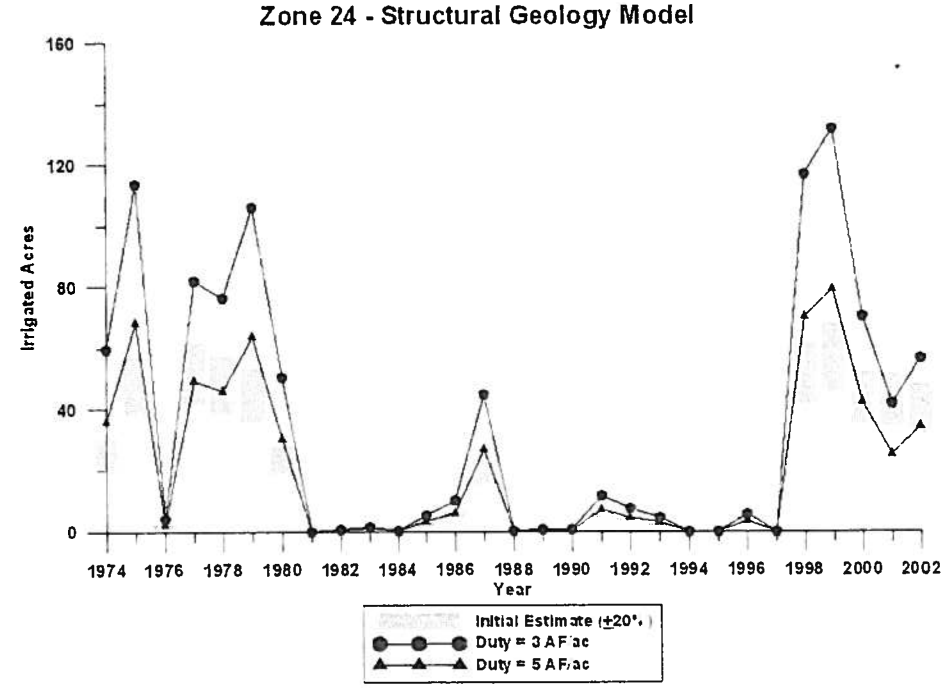




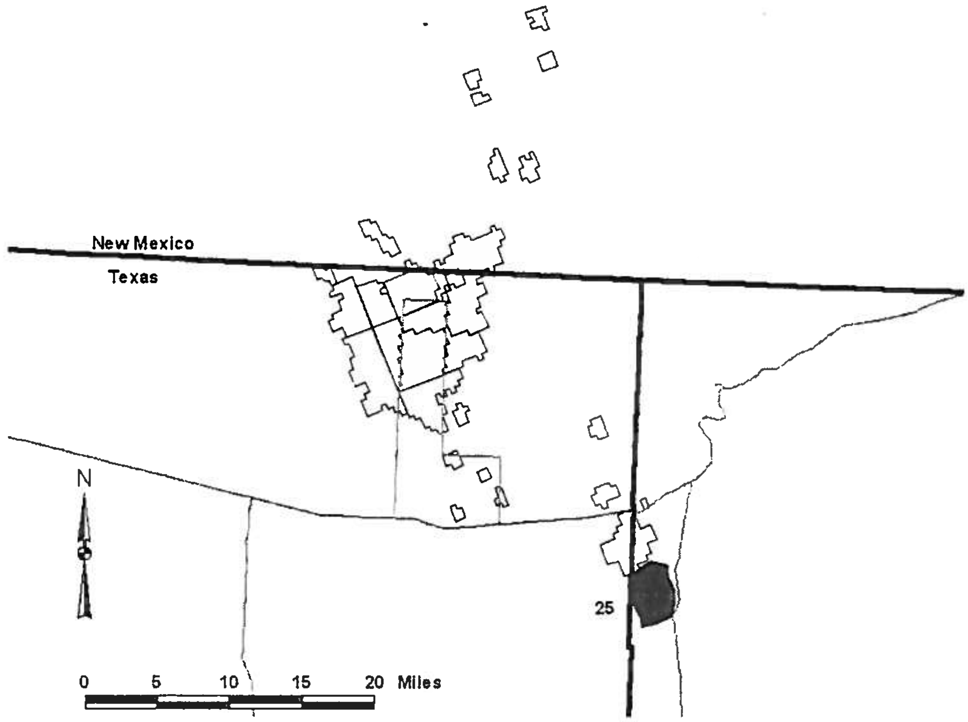
Note: Initial Estimate Range from Groeneveld and Baugh (2002)

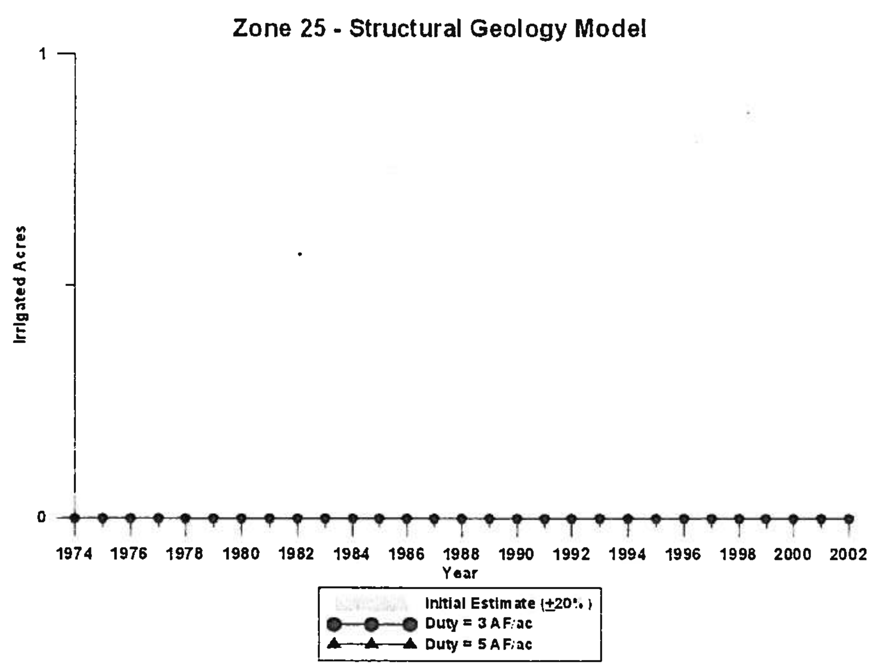


Zone 24 - Structural Geology Model



Note: Initial Estimate Range from Groeneveld and Baugh (2002)

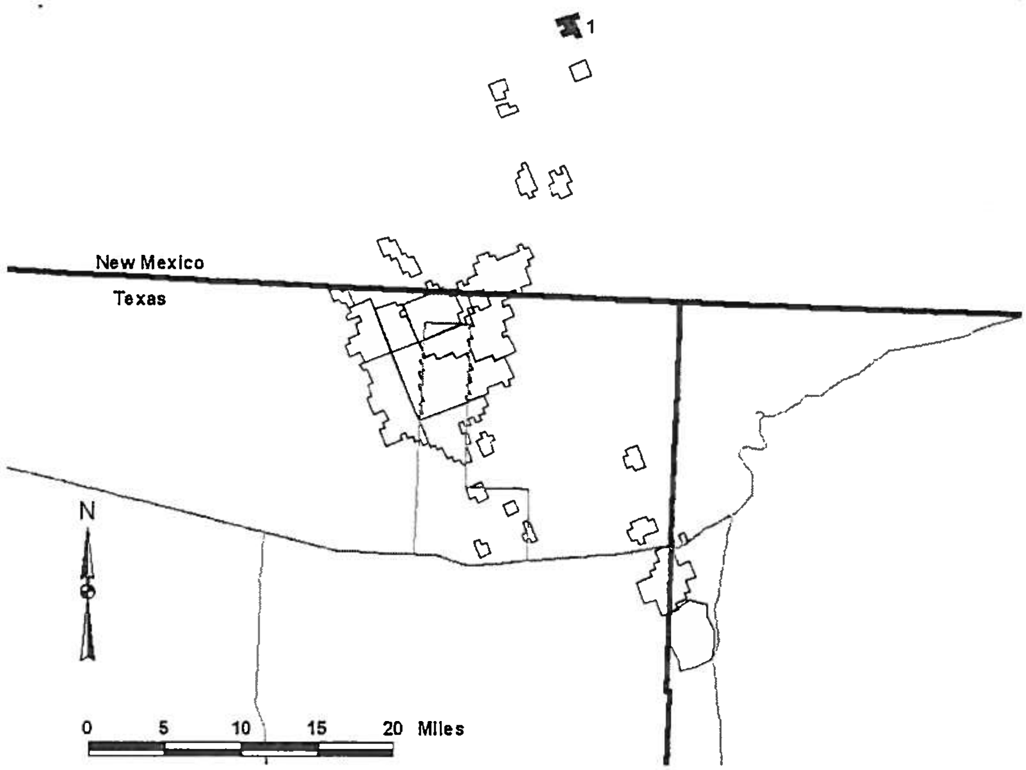




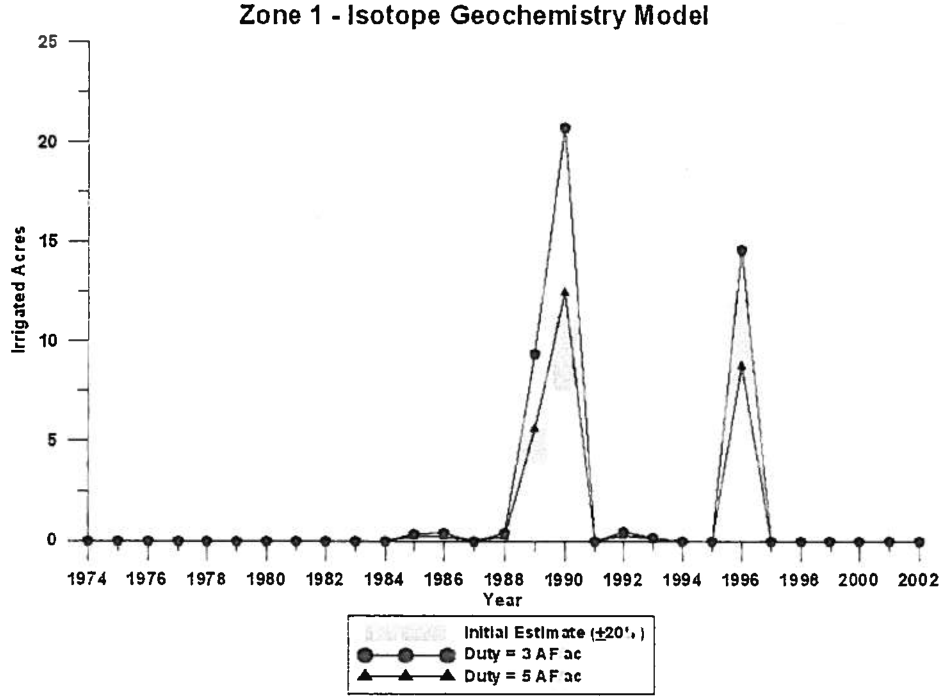
Note: Initial Estimate Range from Groeneveld and Baugh (2002)

Appendix B-2

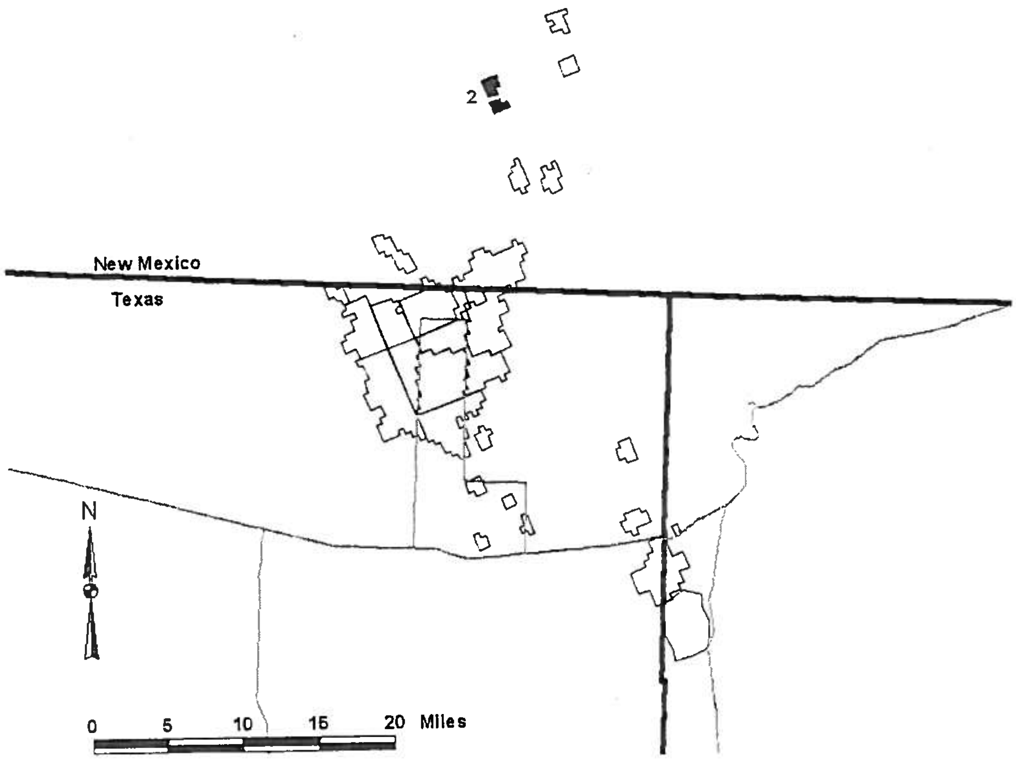
Irrigated Acreage Estimates for Each Pumping Zone
Isotope Geochemistry Model

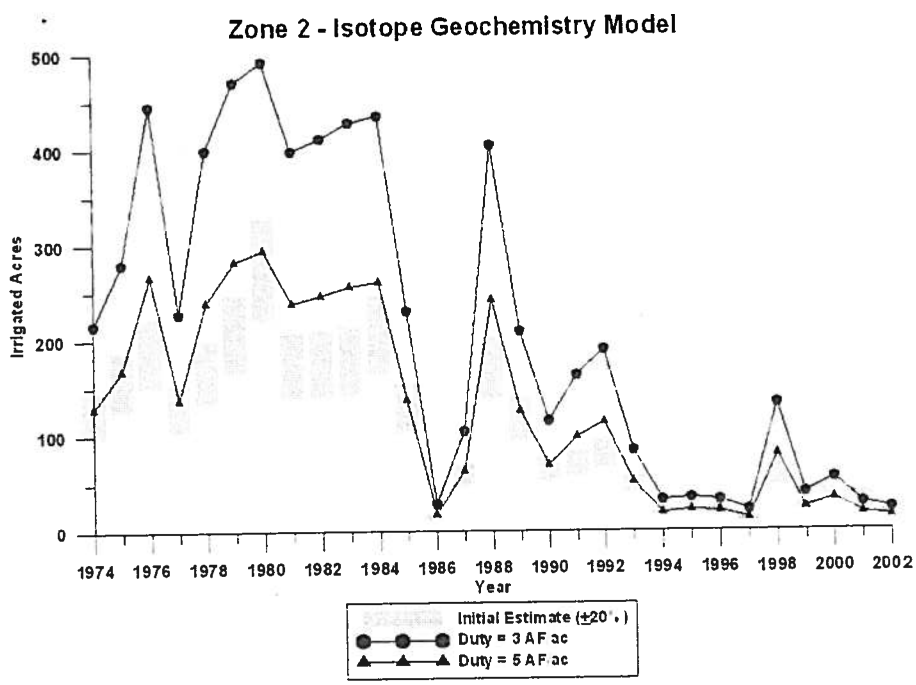


Zone 1 - Isotope Geochemistry Model

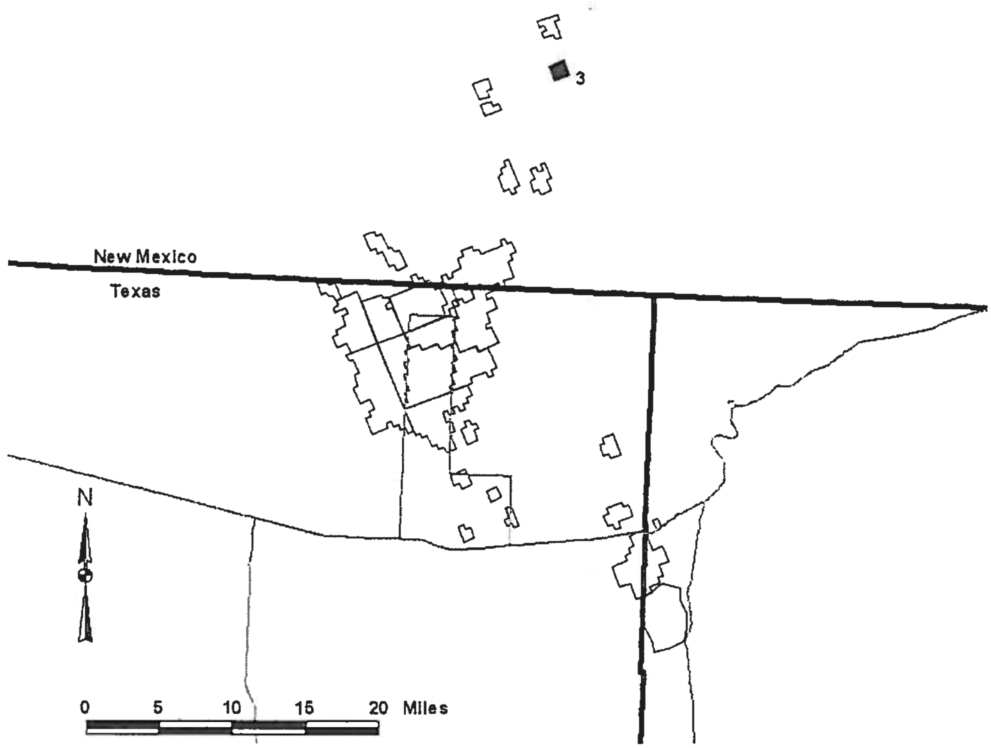


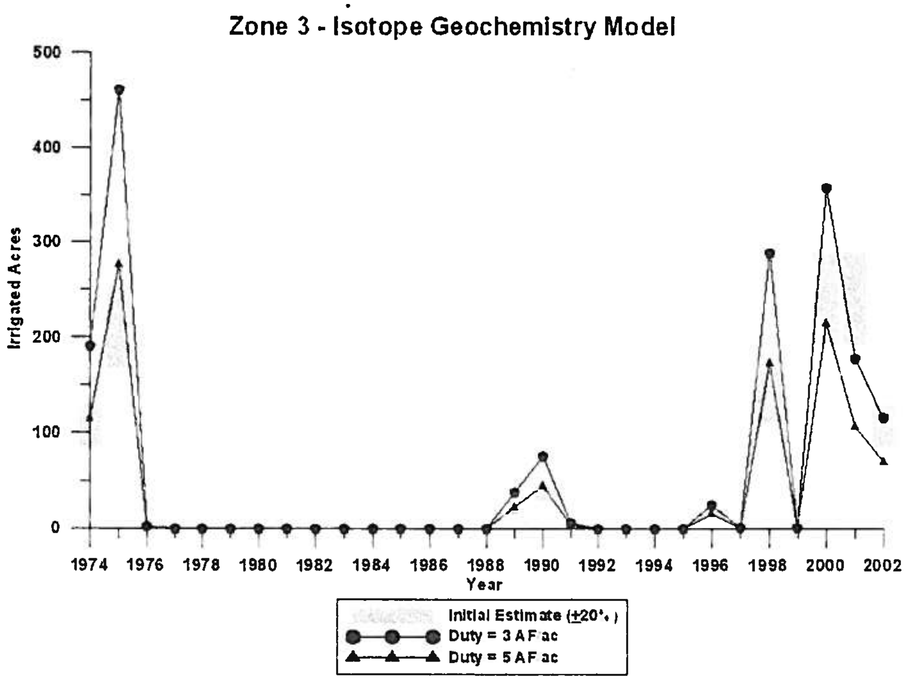
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



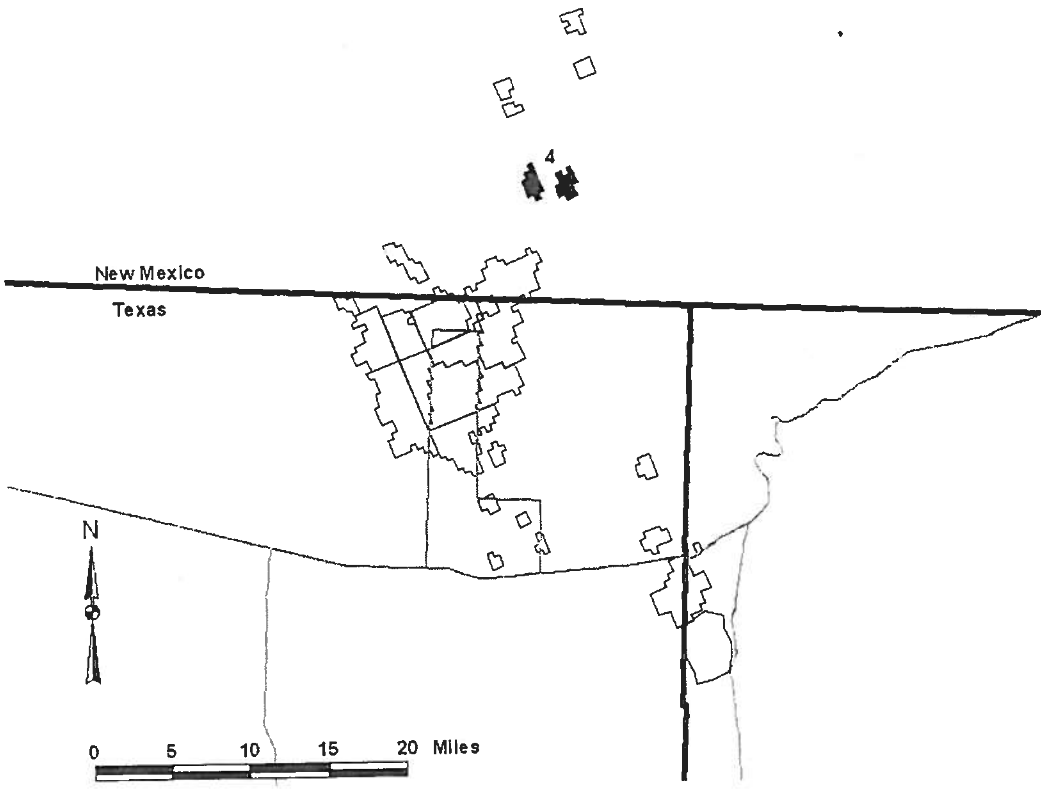


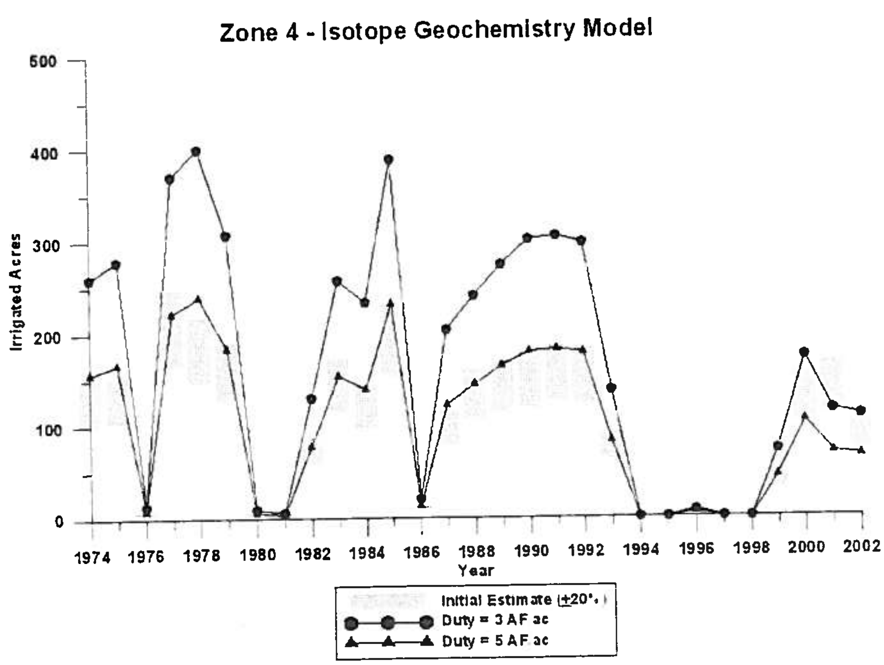
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



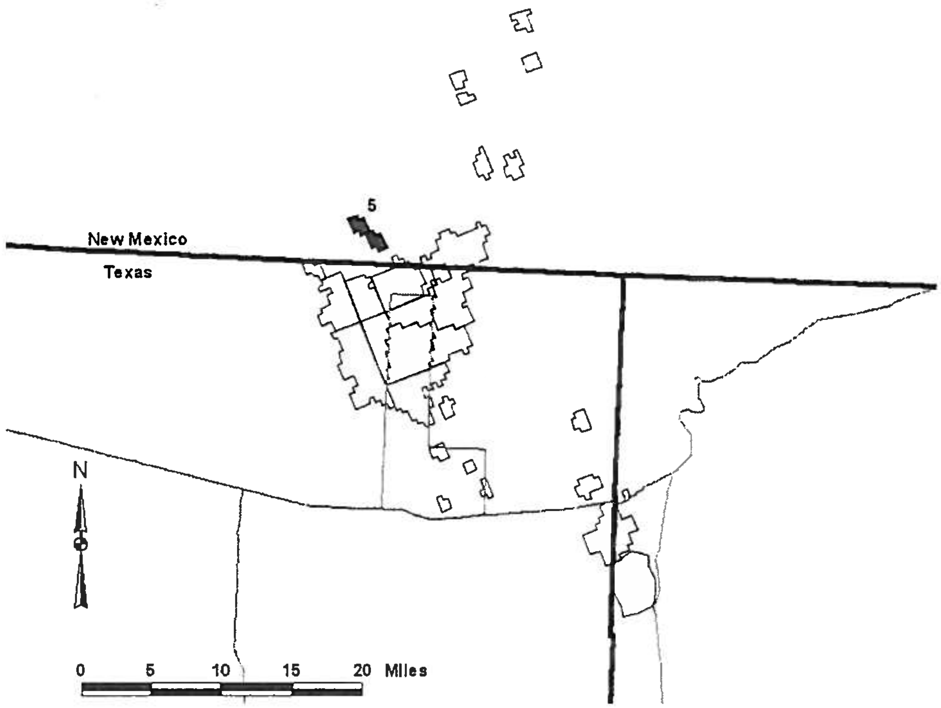


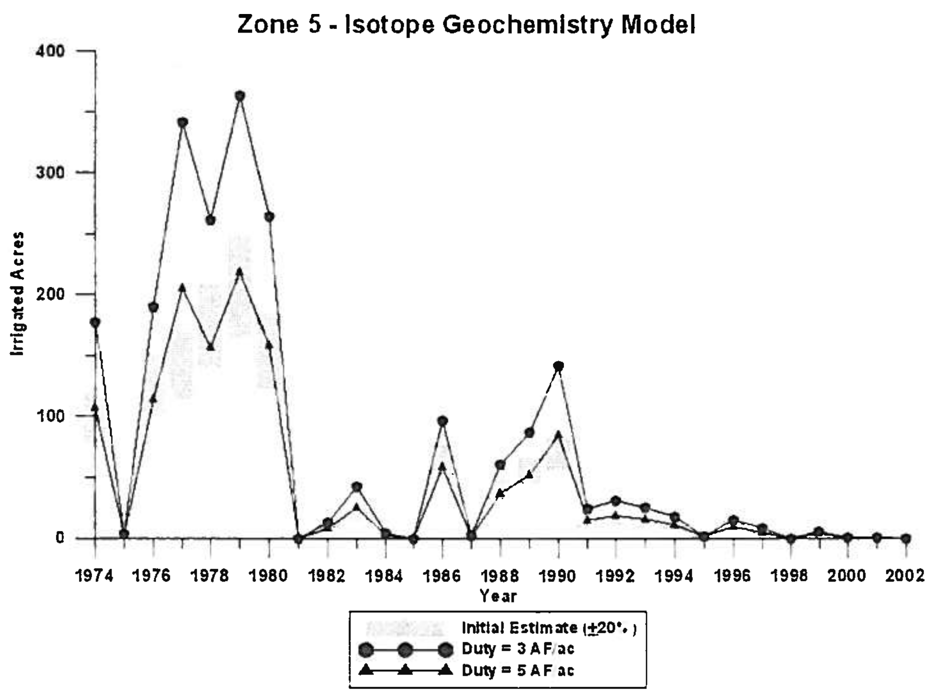
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



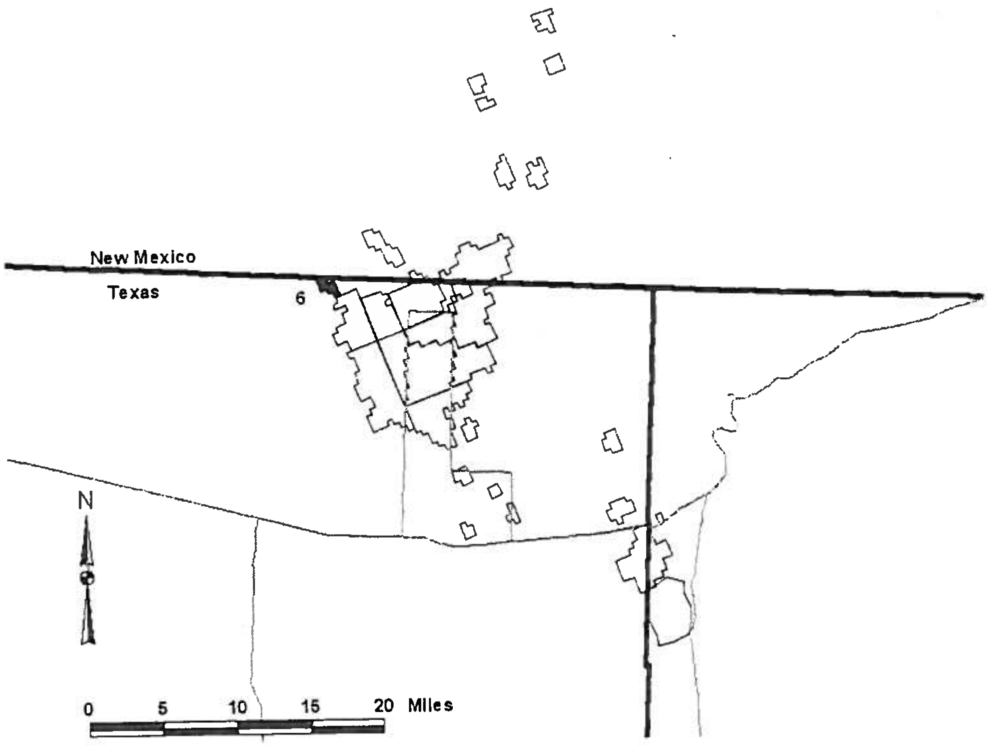


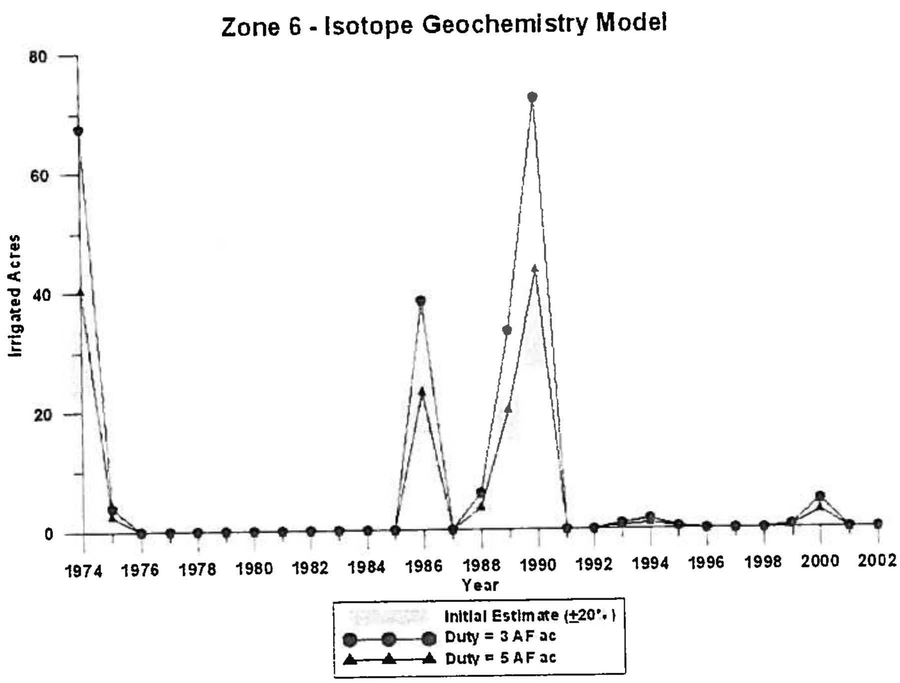
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



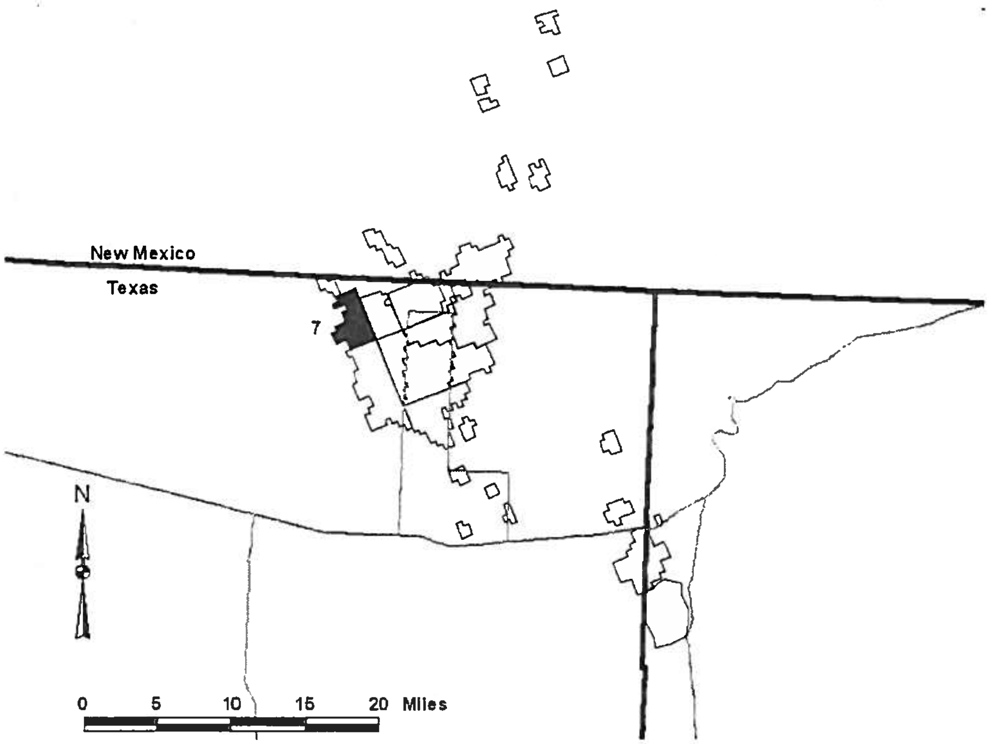


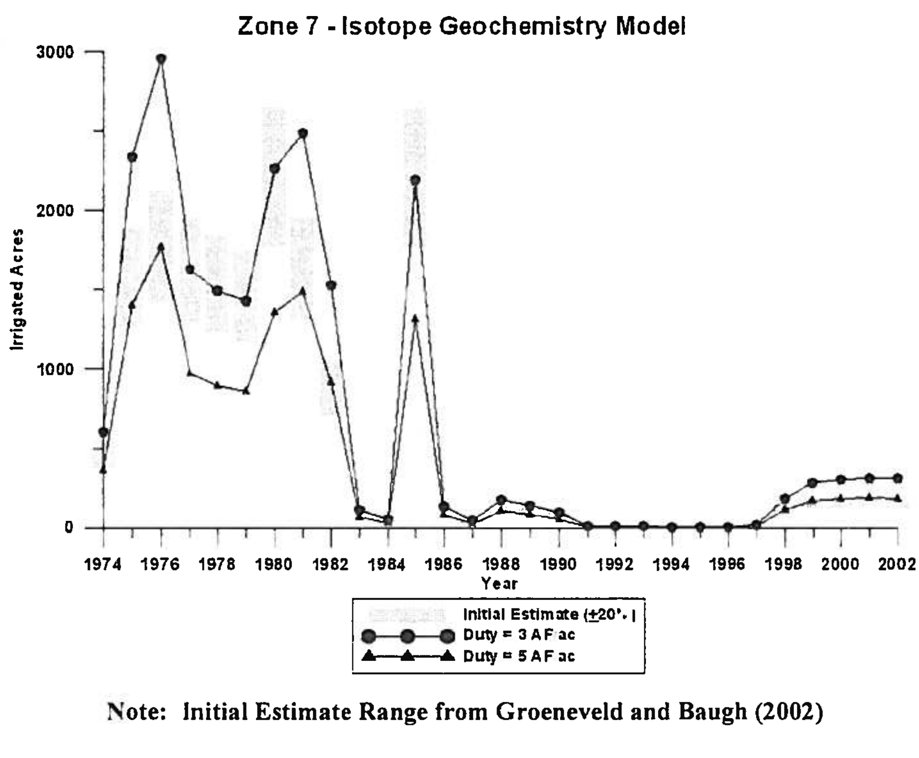
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



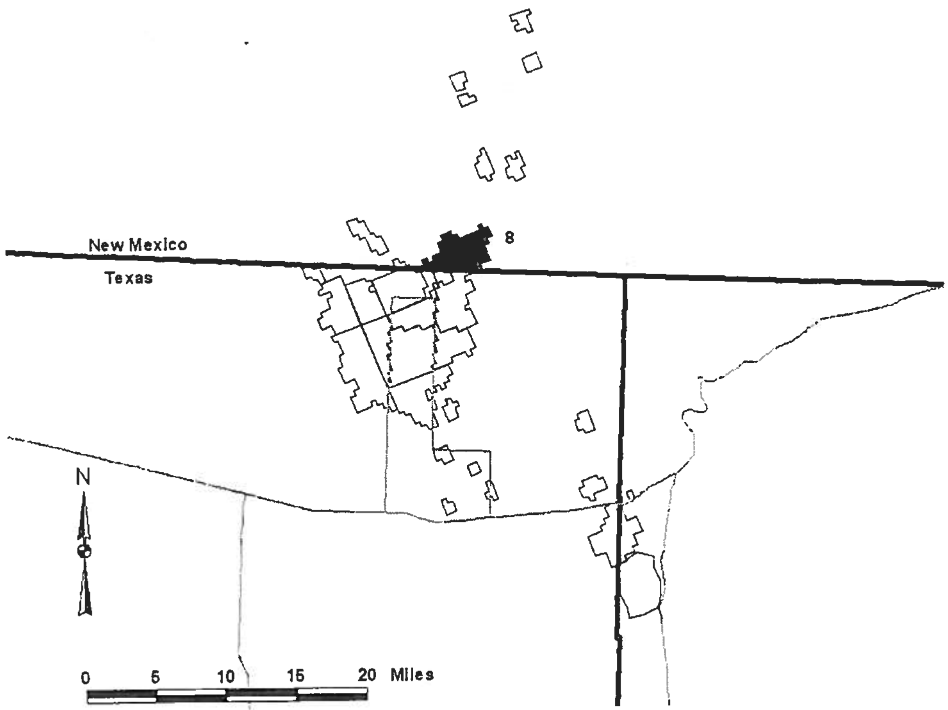


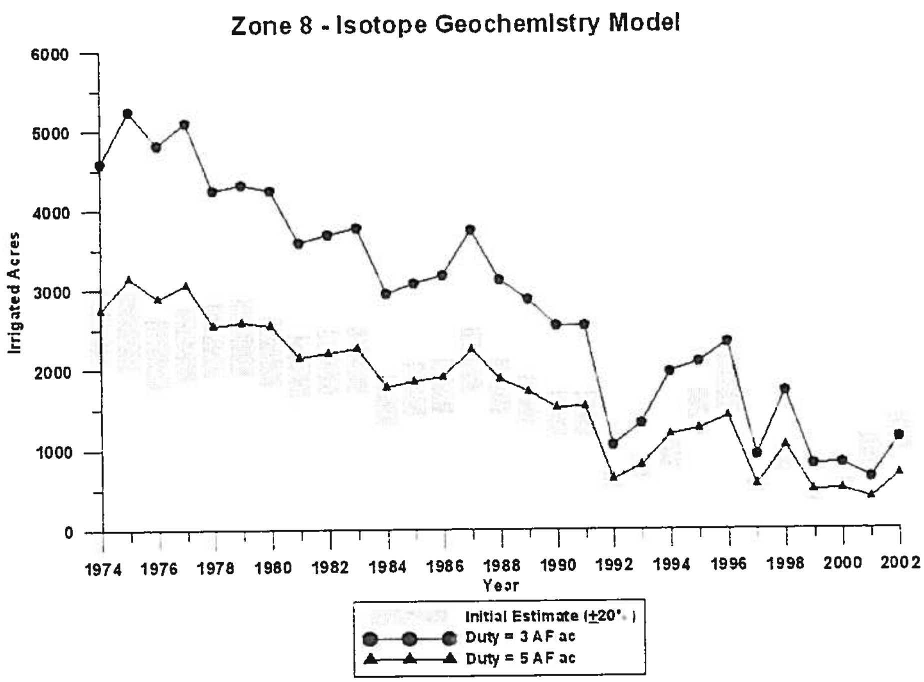
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



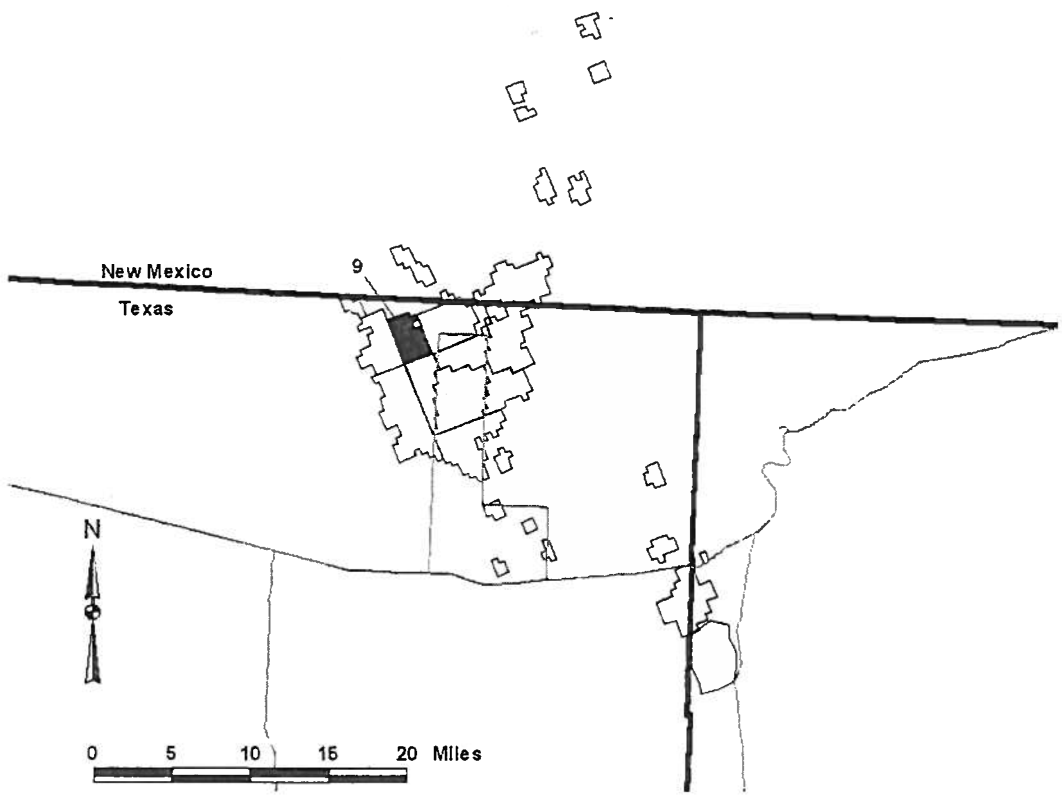


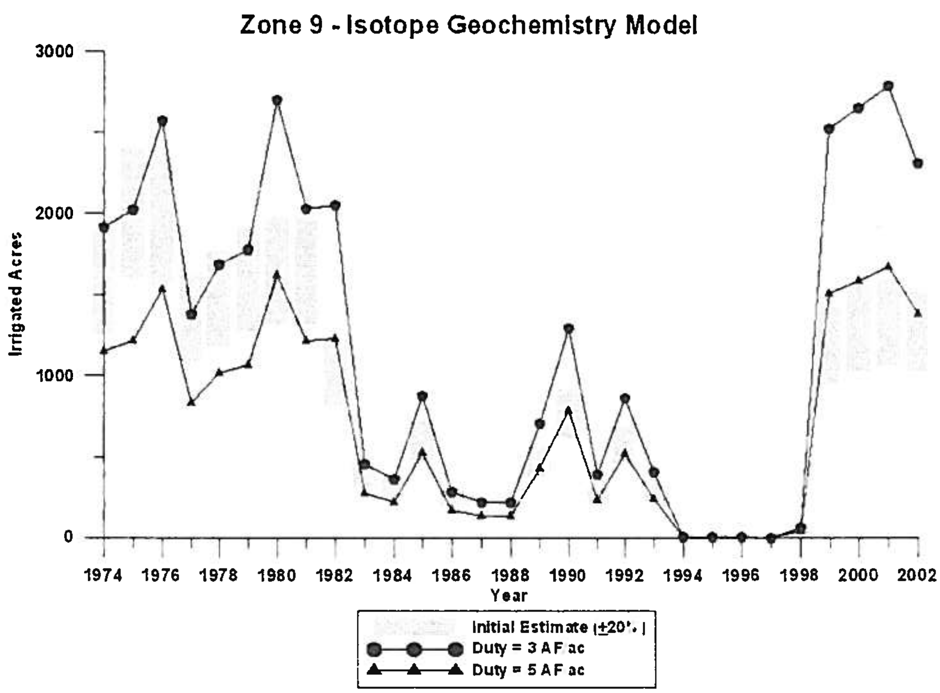
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



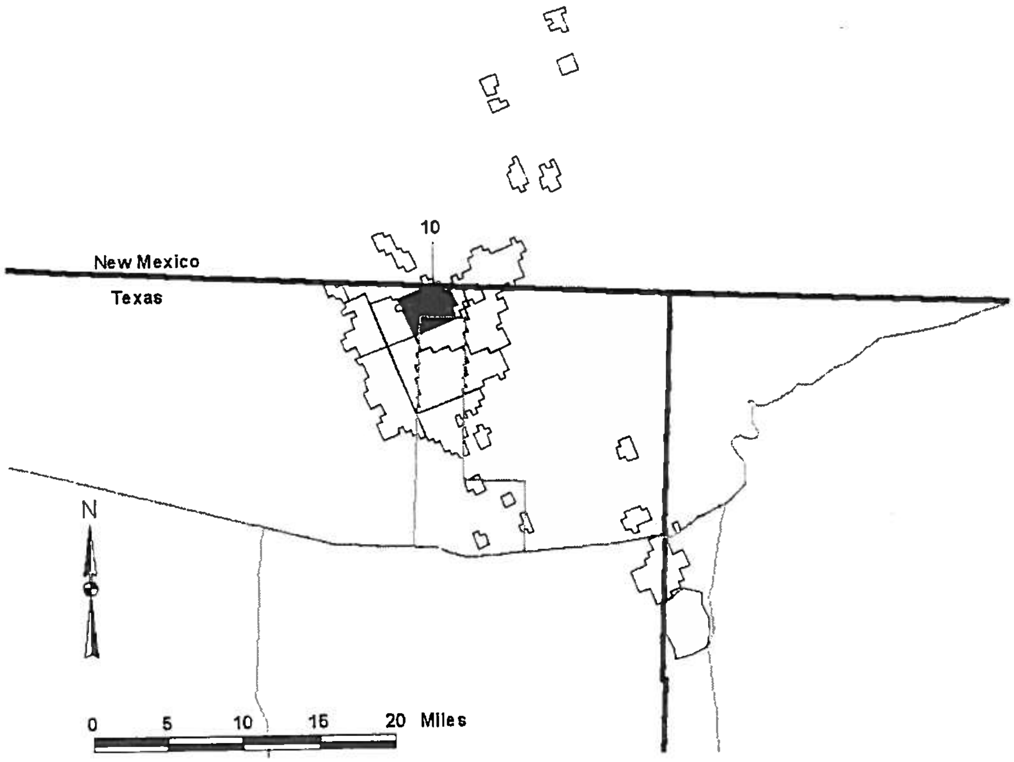


Note: Initial Estimate Range from Groeneveld and Baugh (2002)

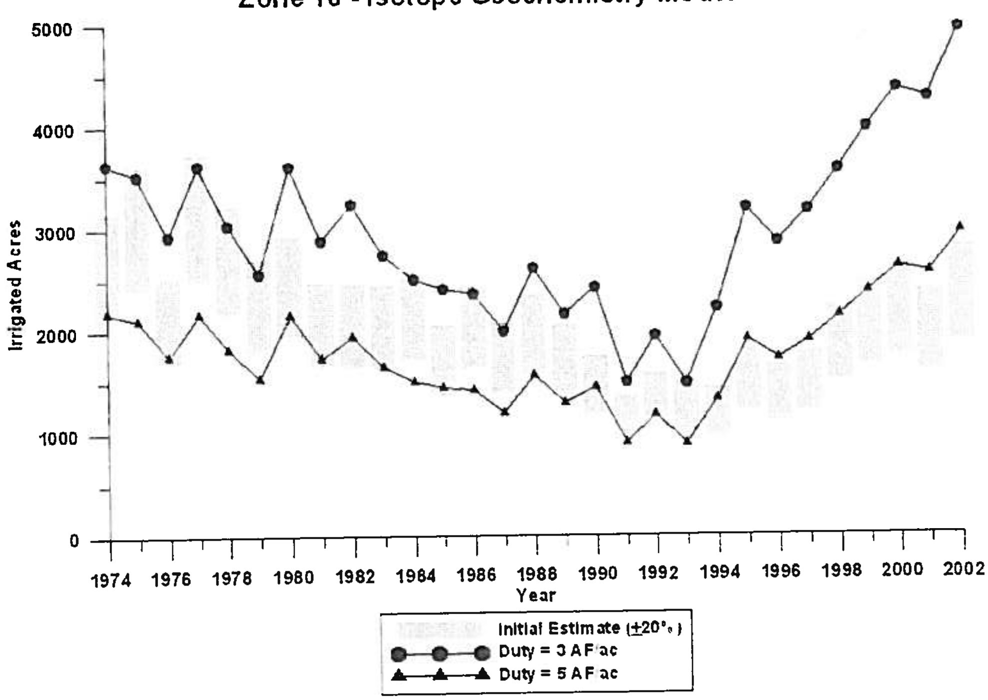




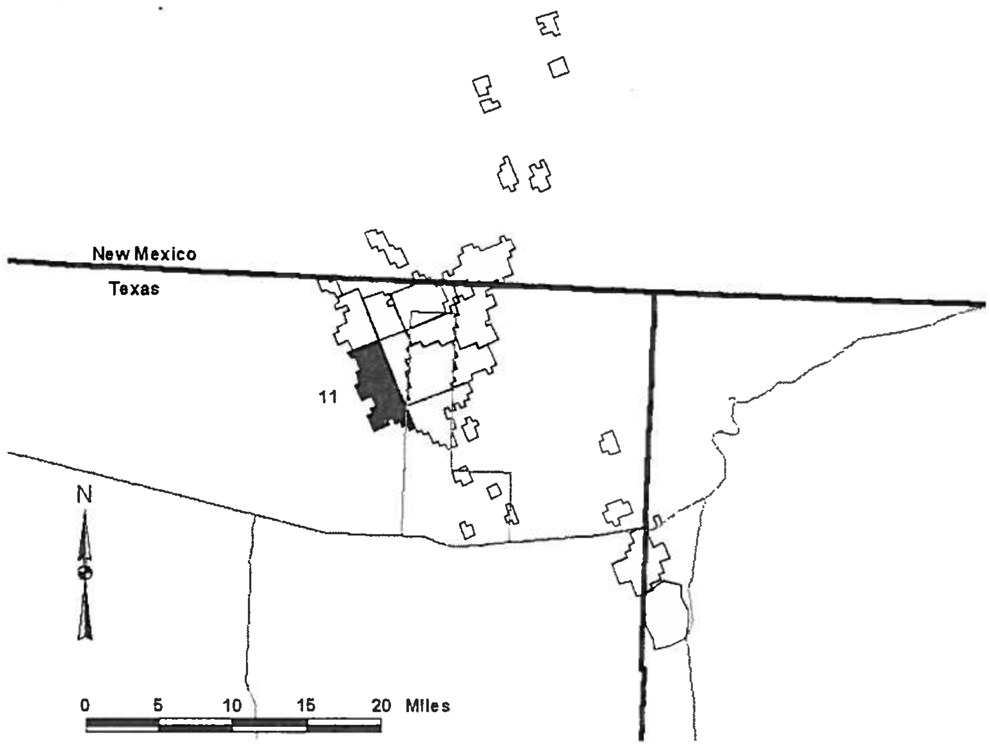
Note: Initial Estimate Range from Groeneveld and Baugh (2002)

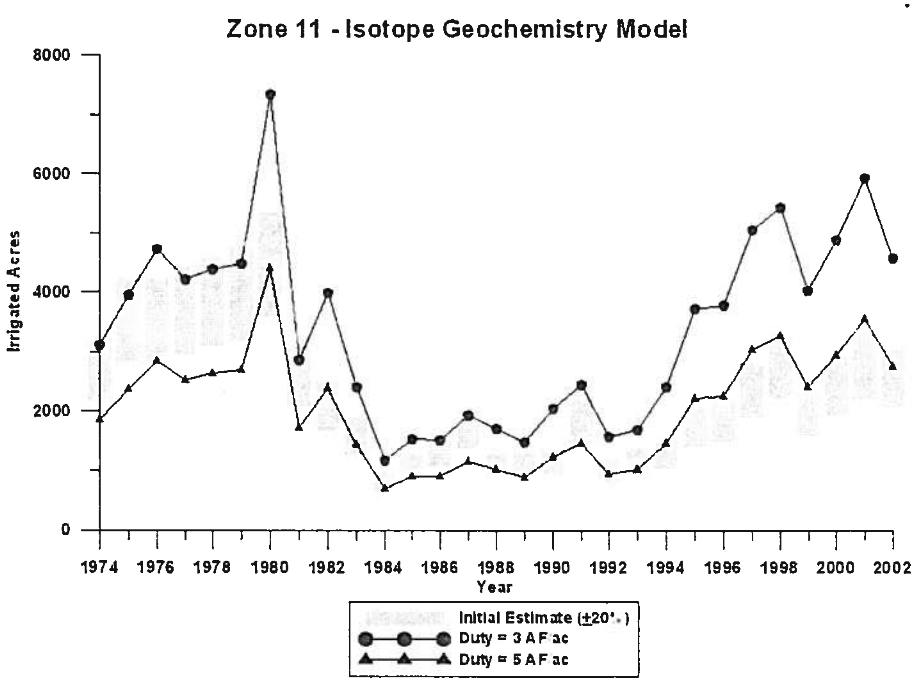


Zone 10 - Isotope Geochemistry Model

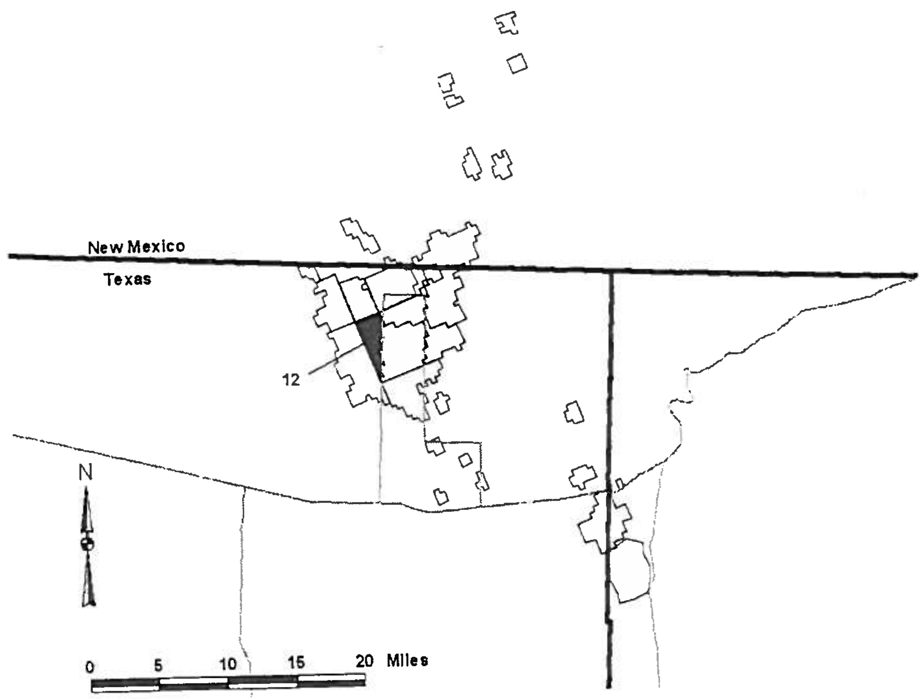


Note: Initial Estimate Range from Groeneveld and Baugh (2002)

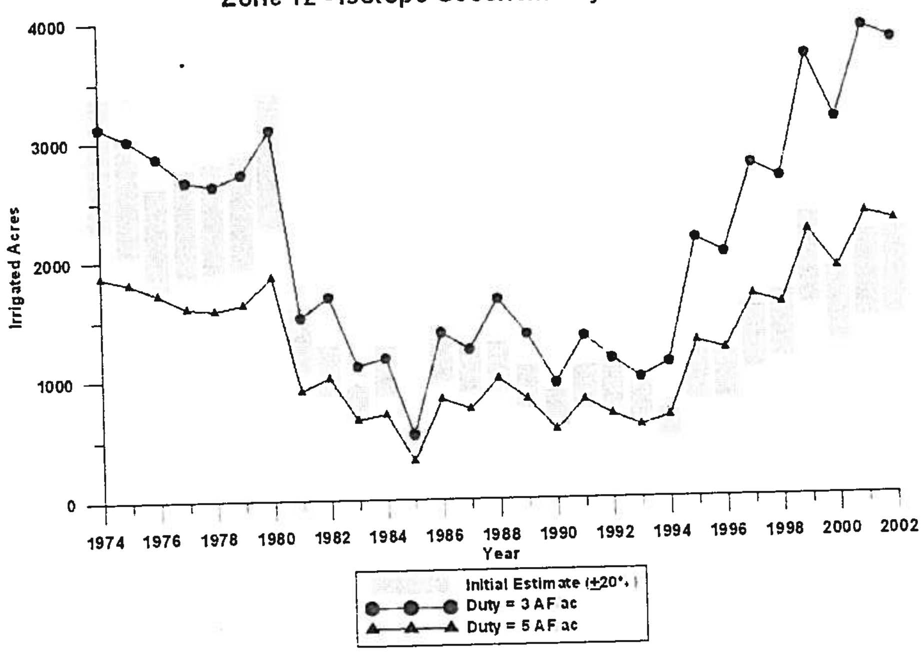




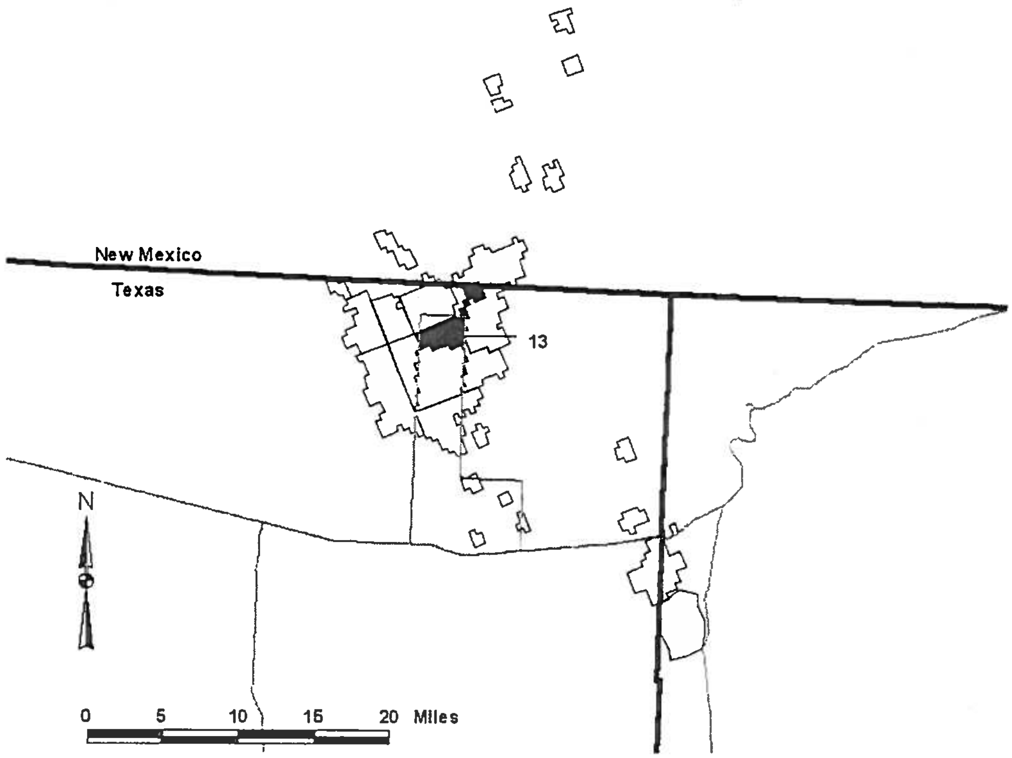
Note: Initial Estimate Range from Groeneveld and Baugh (2002)

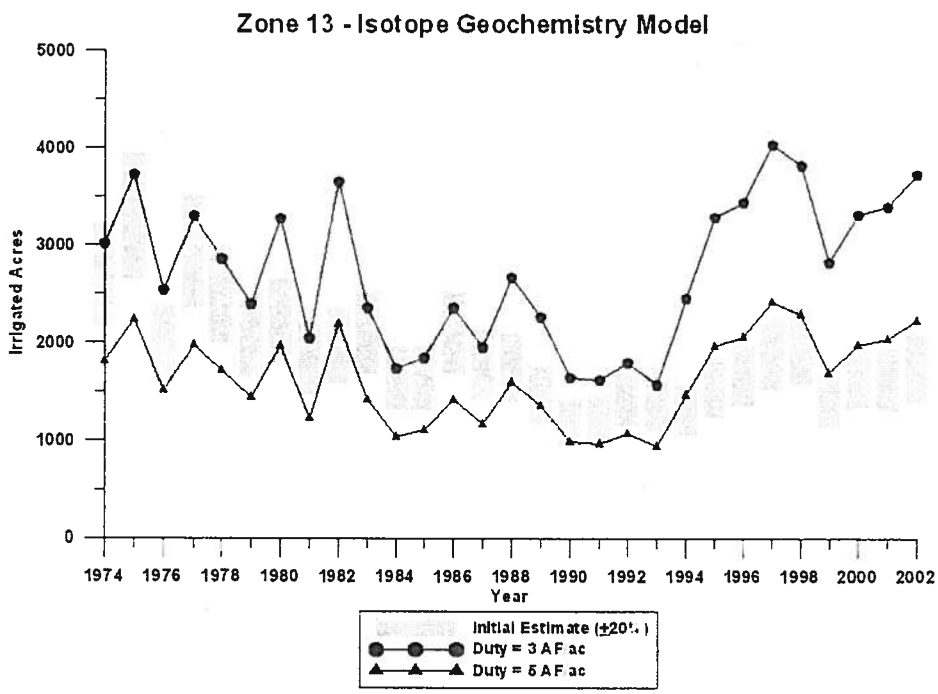


Zone 12 - Isotope Geochemistry Model

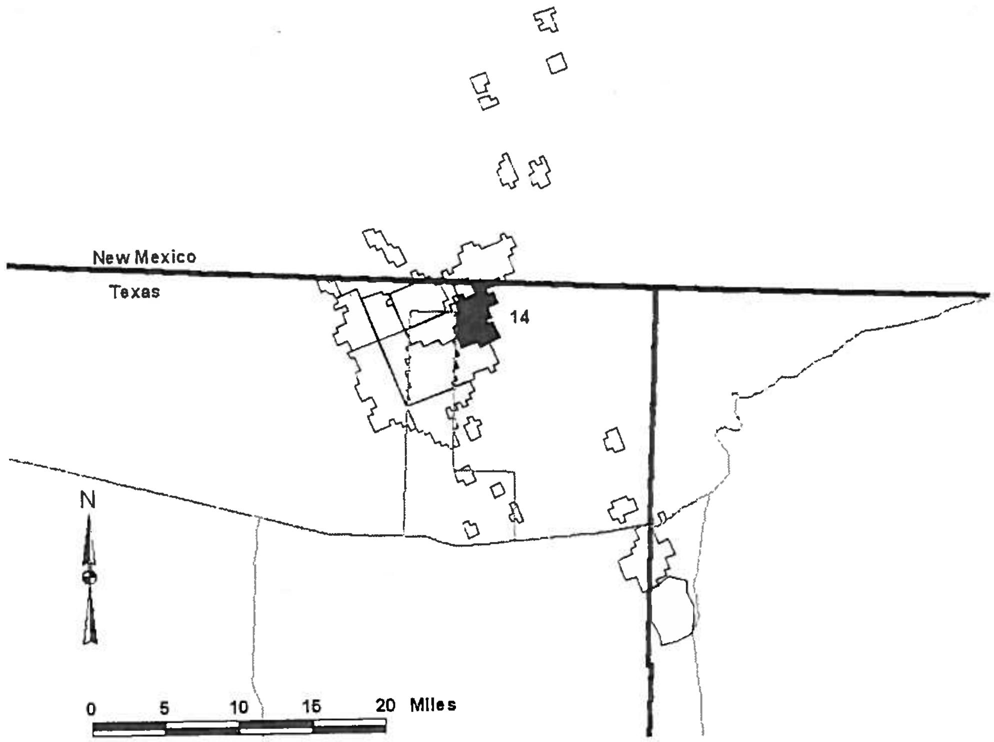


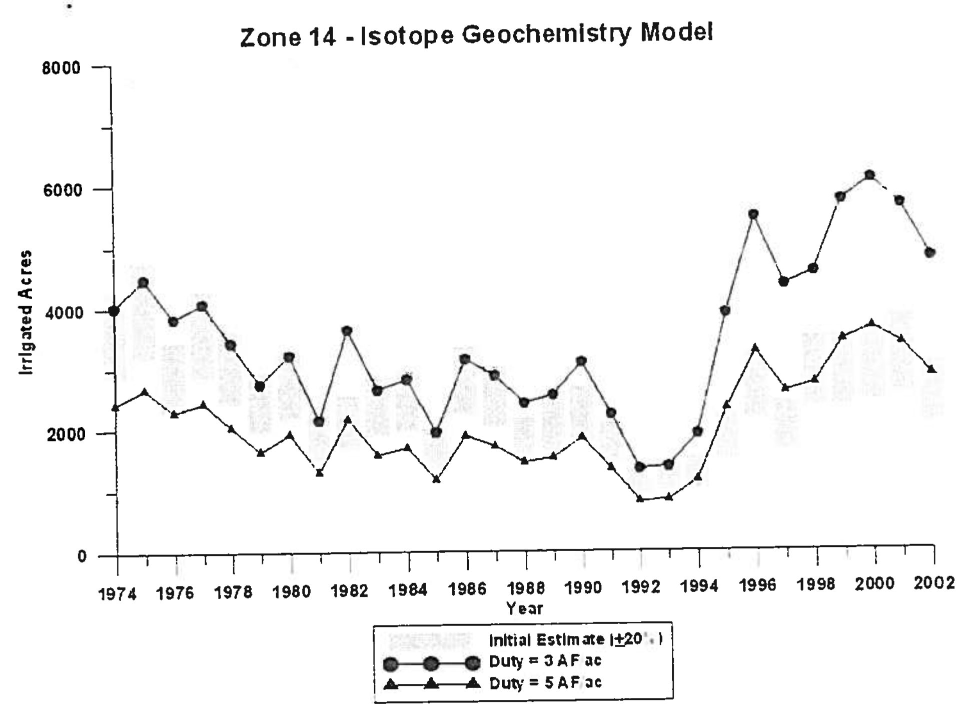
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



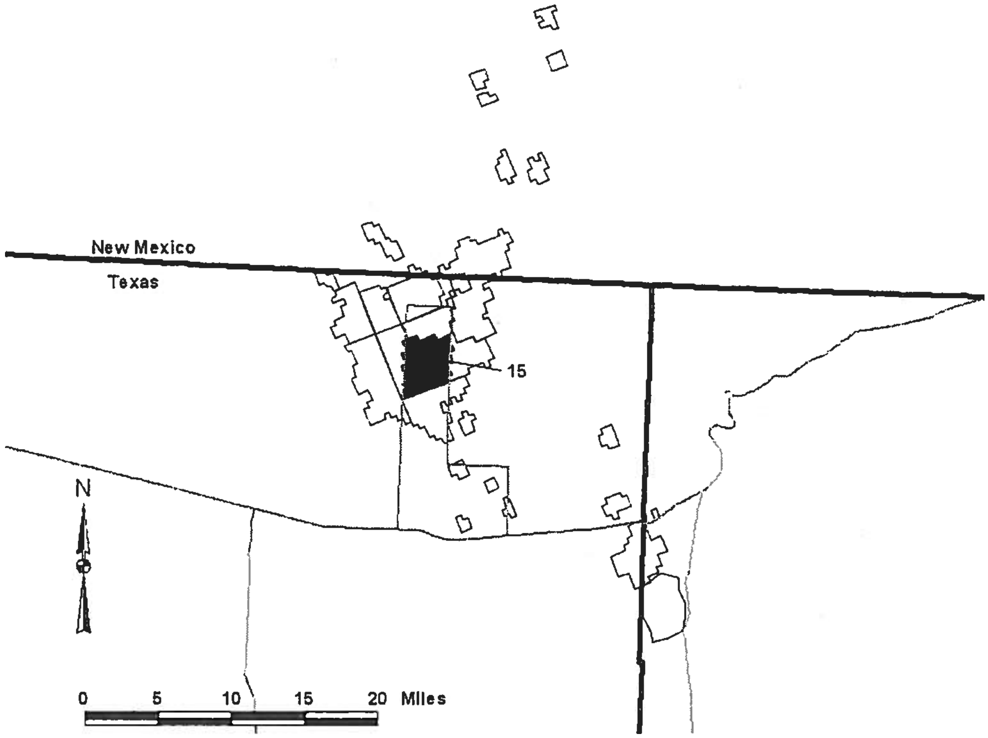


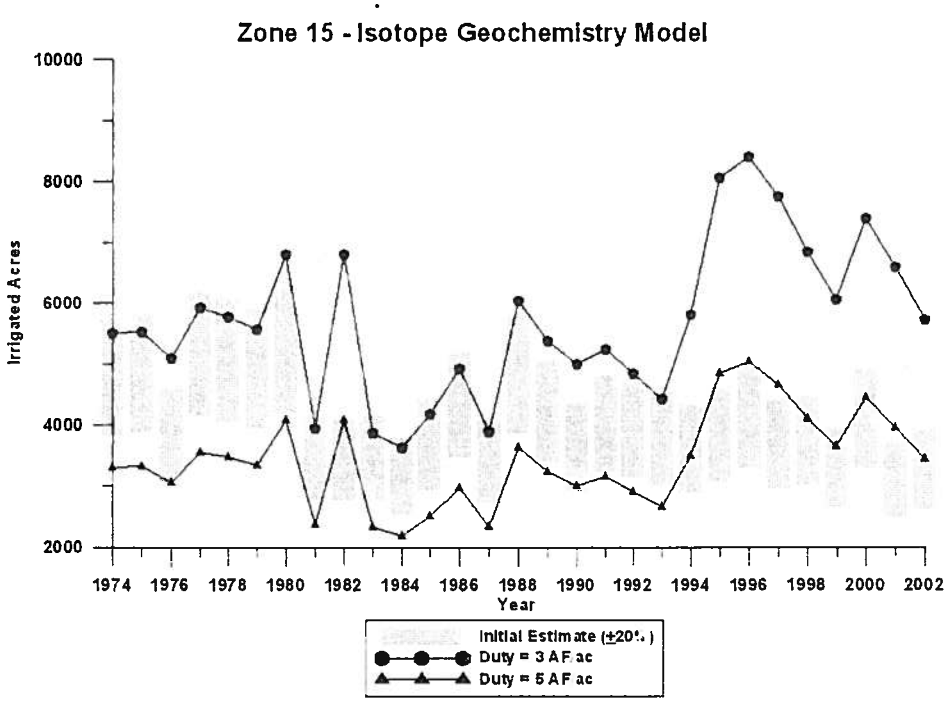
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



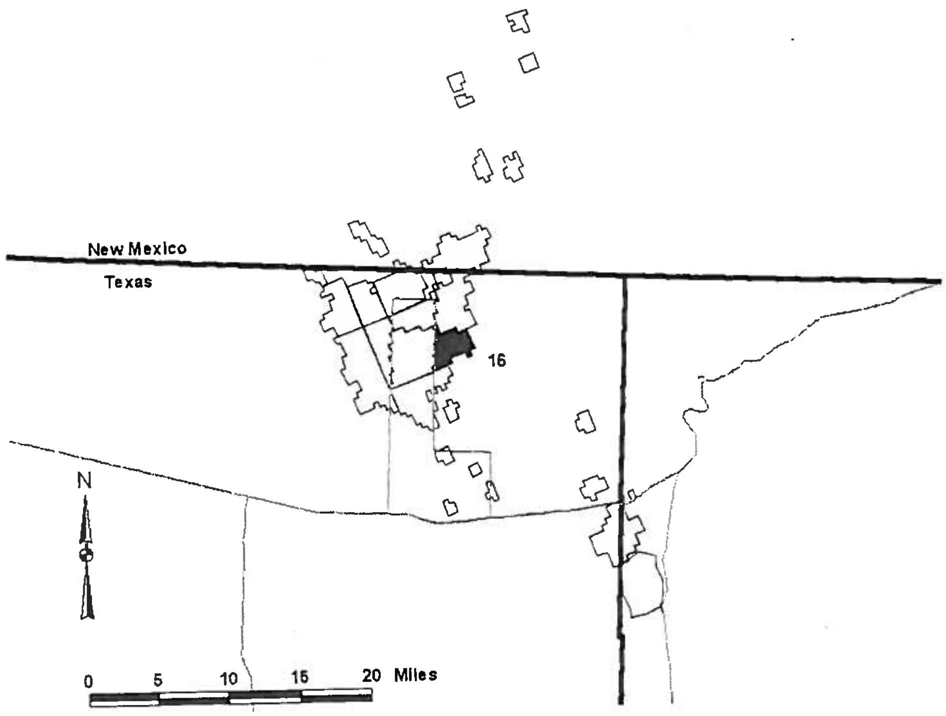


Note: Initial Estimate Range from Groeneveld and Baugh (2002)

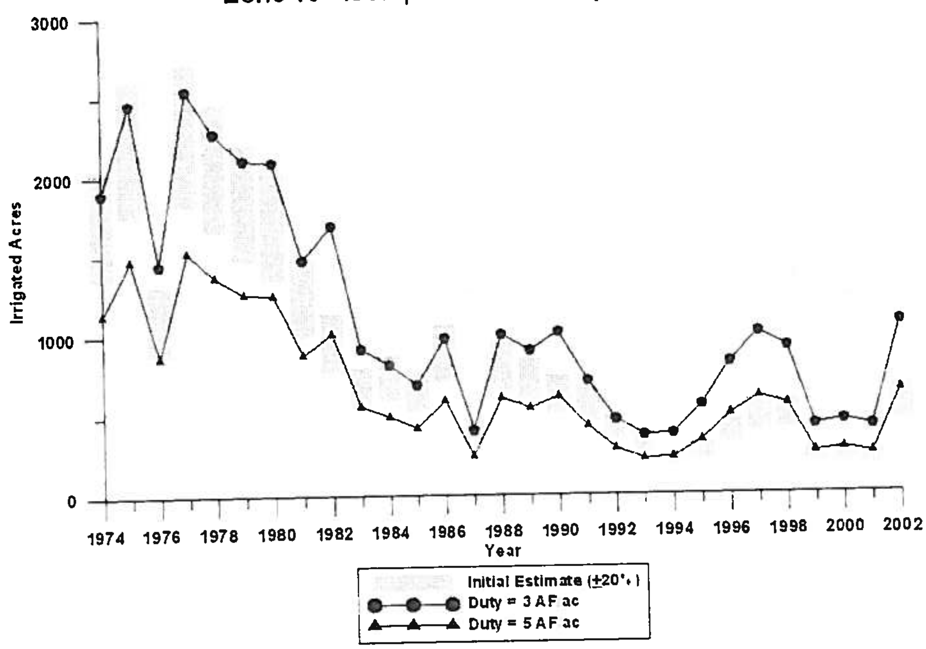




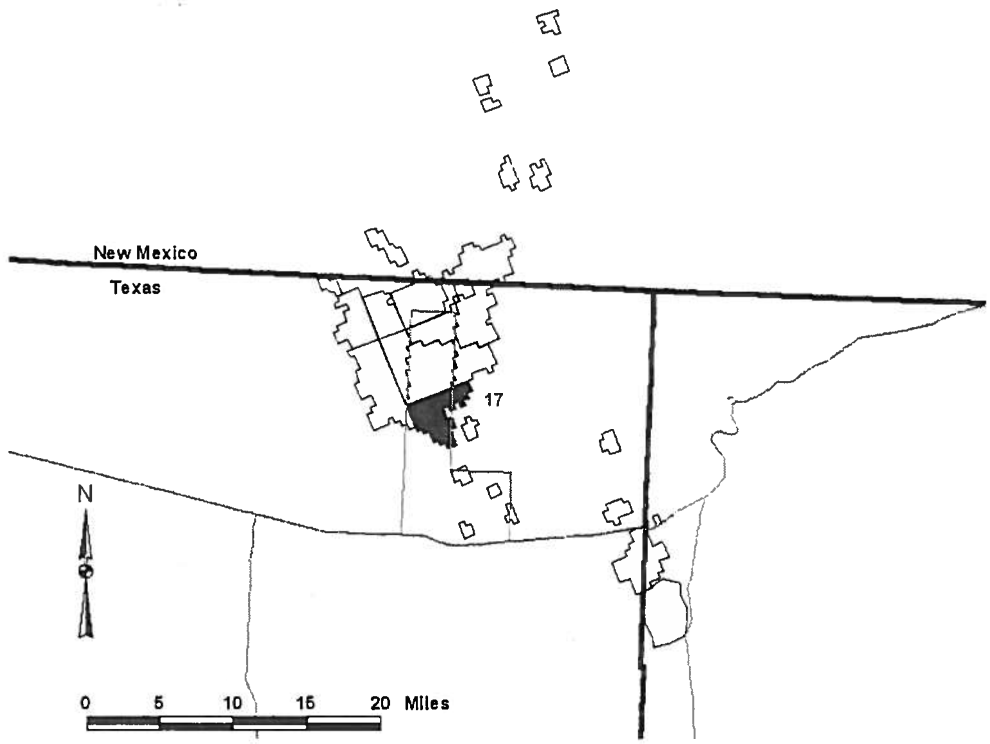
Note: Initial Estimate Range from Groeneveld and Baugh (2002)

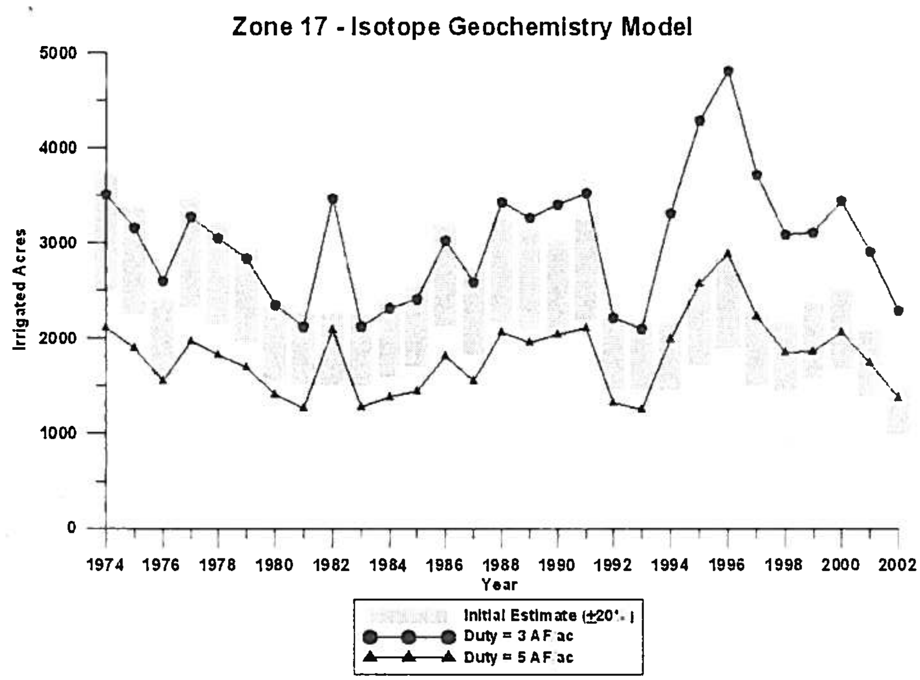


Zone 16 - Isotope Geochemistry Model

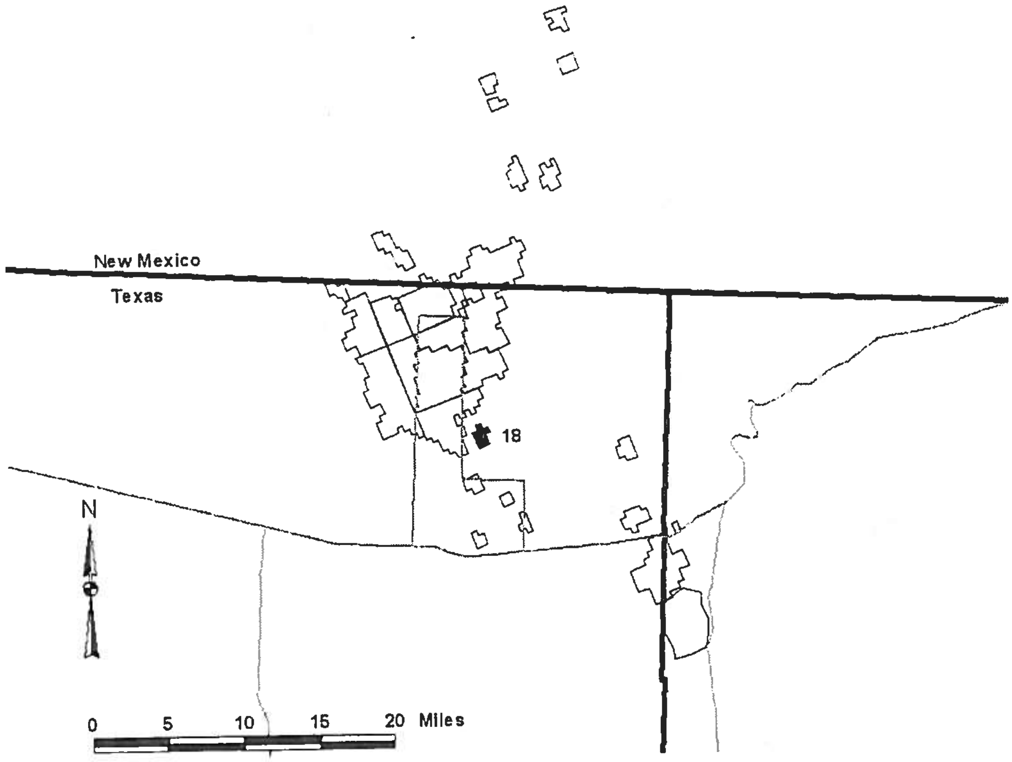


Note: Initial Estimate Range from Groeneveld and Baugh (2002)

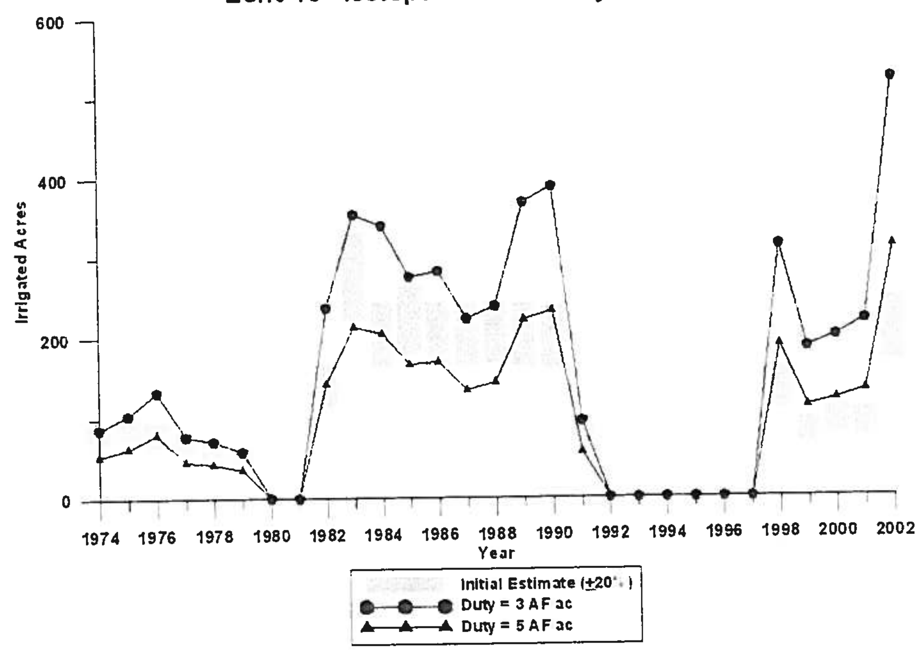




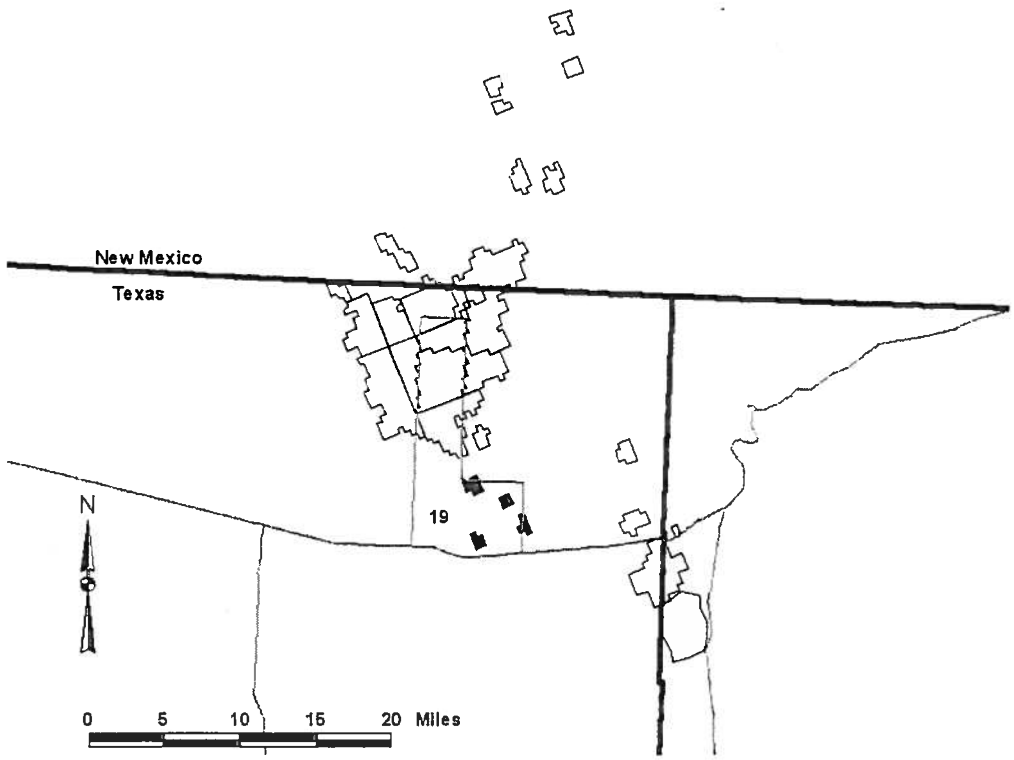
Note: Initial Estimate Range from Groeneveld and Baugh (2002)

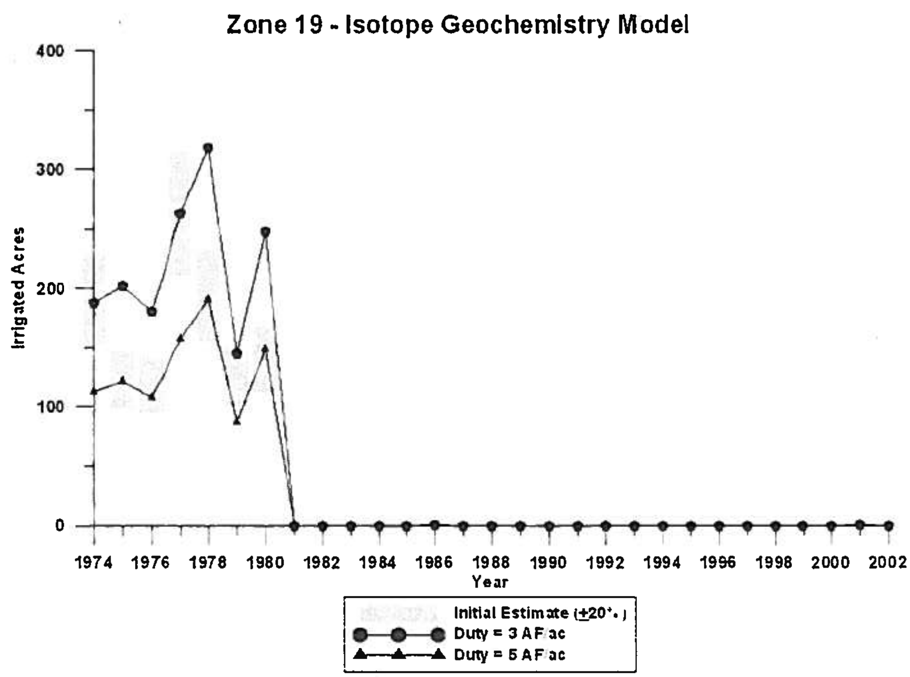


Zone 18 - Isotope Geochemistry Model

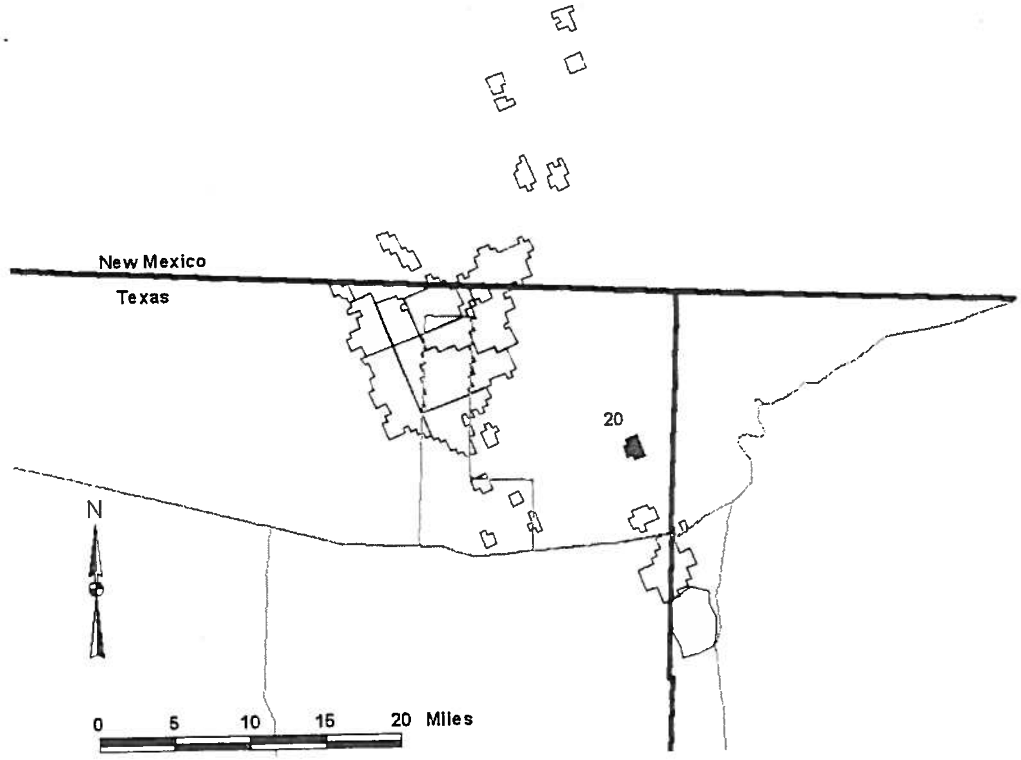


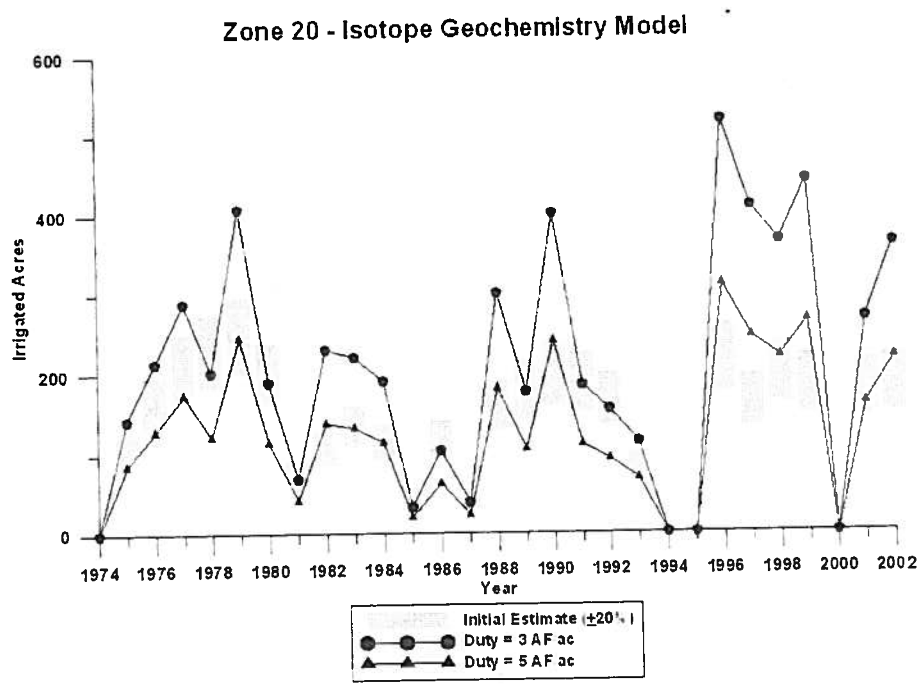
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



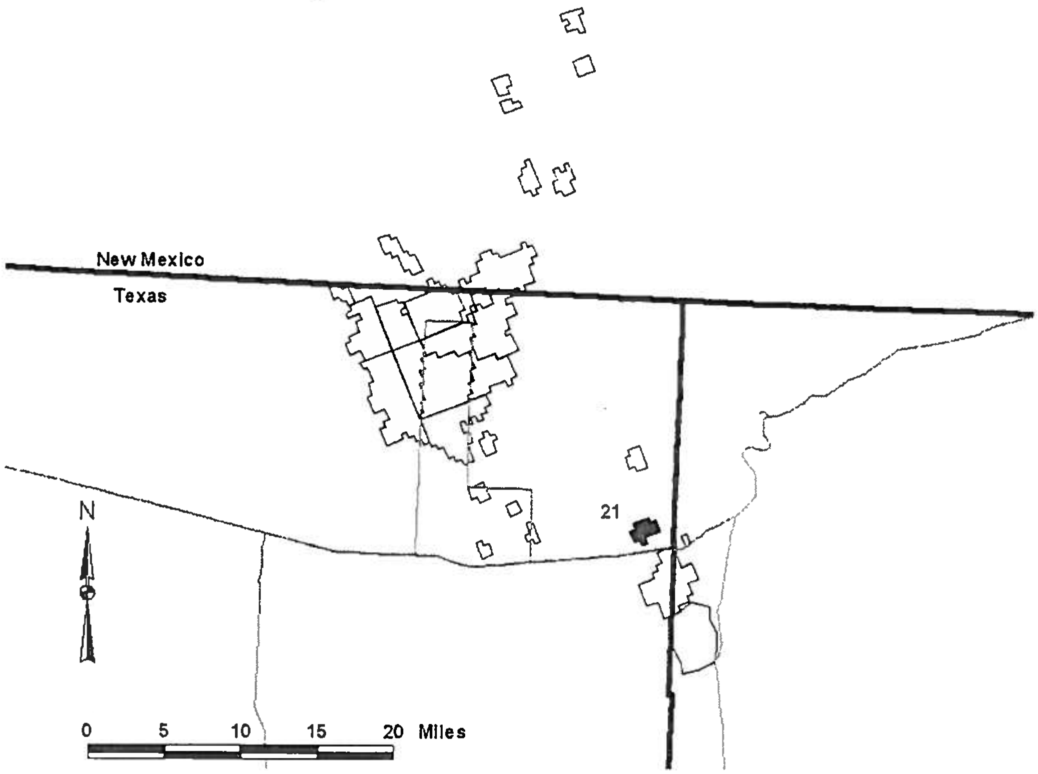


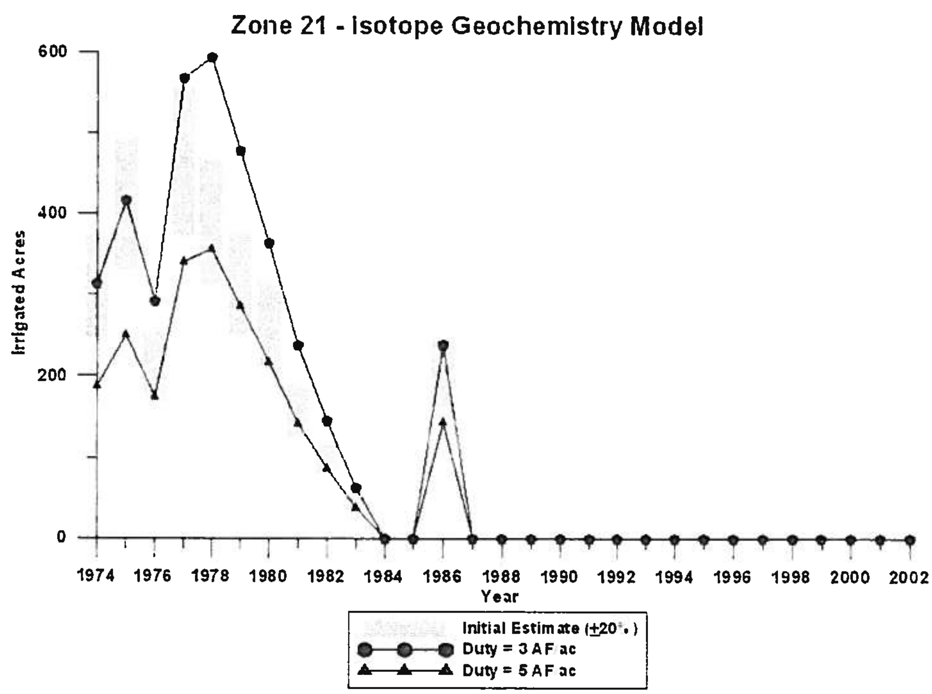
Note: Initial Estimate Range from Groeneveld and Baugh (2002)





Note: Initial Estimate Range from Groeneveld and Baugh (2002)





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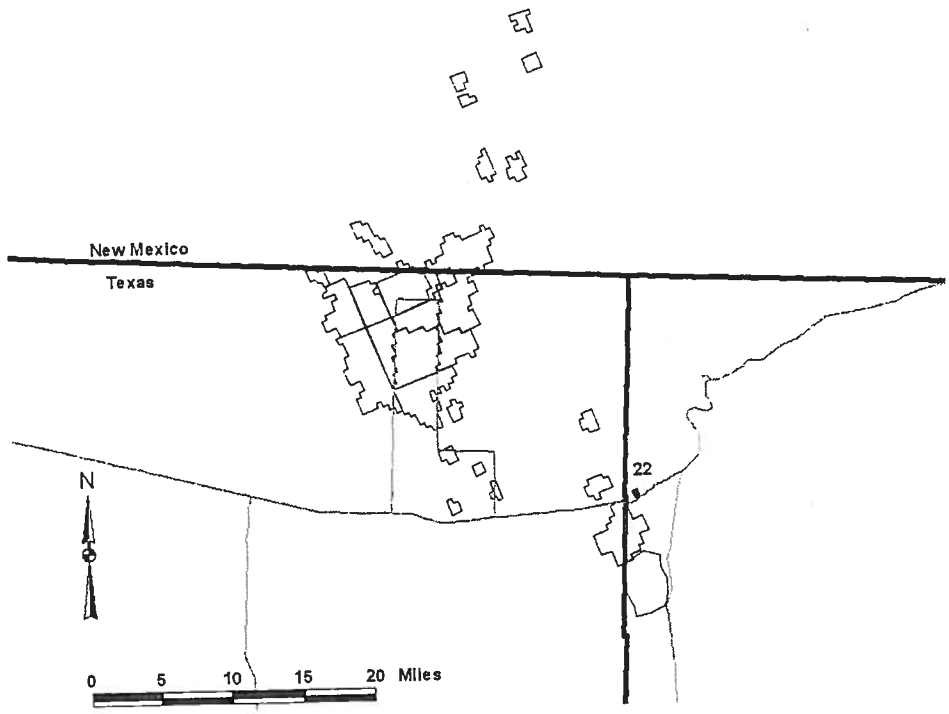
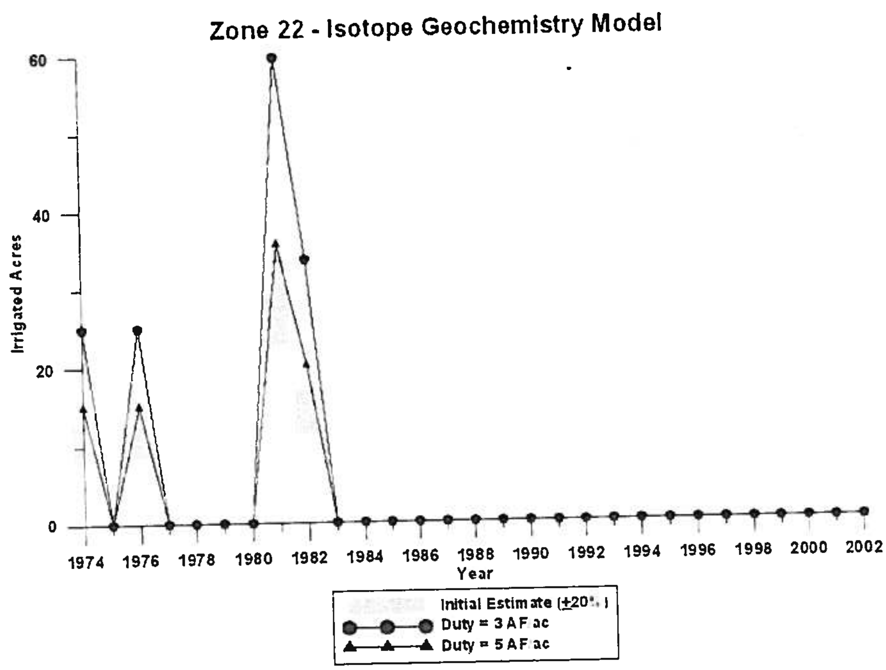
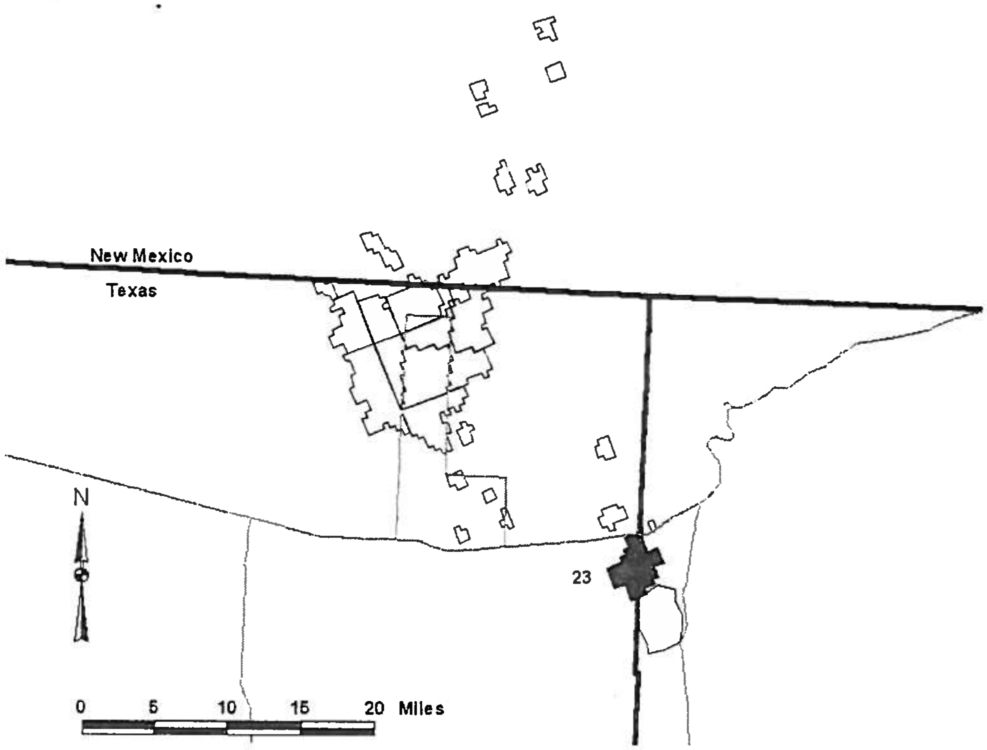
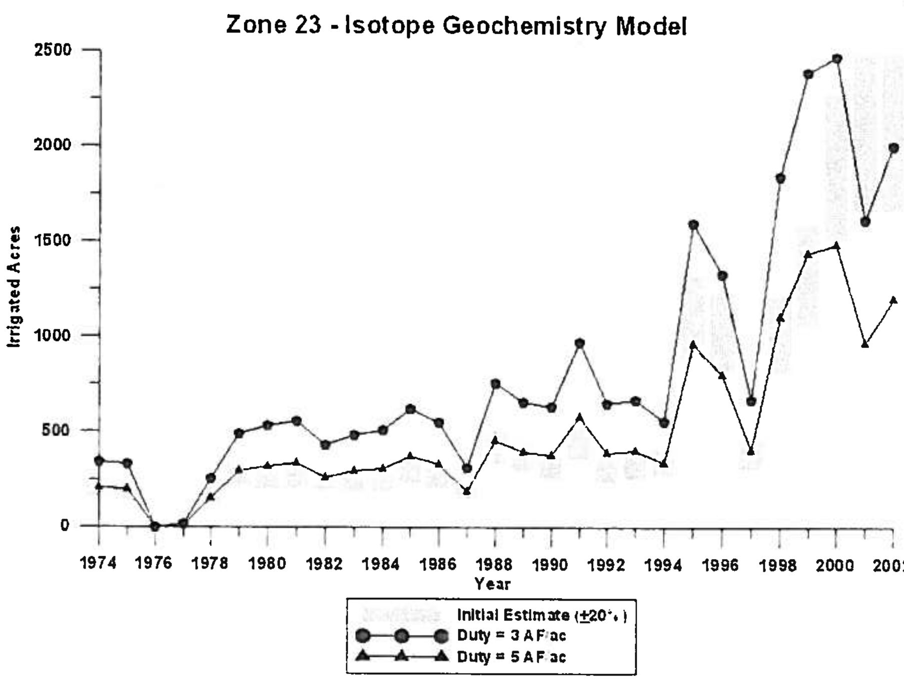




Note: Initial Estimate Range from Groeneveld and Baugh (2002)





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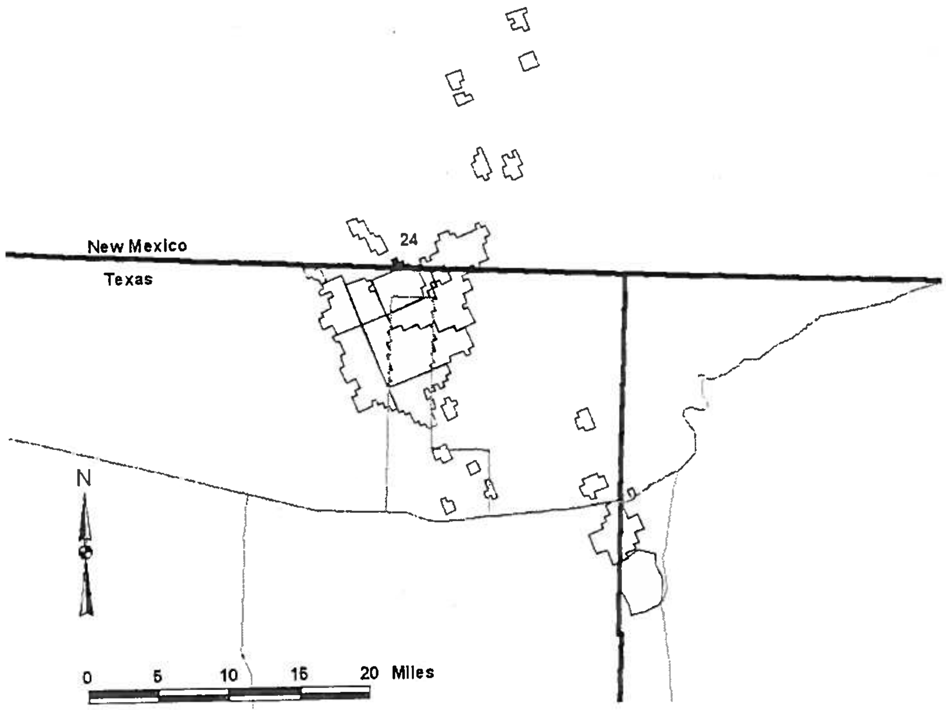
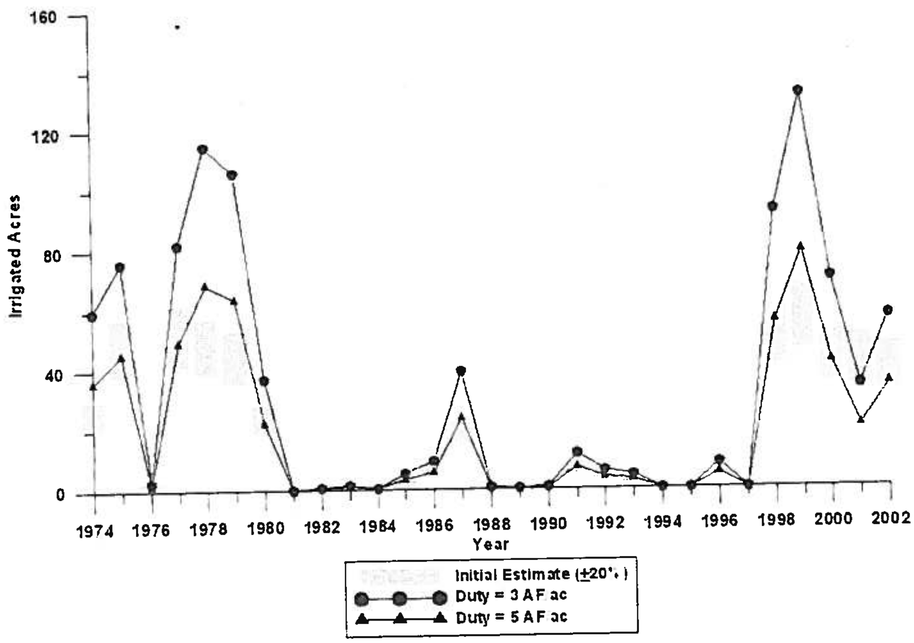


Zone 24 - Isotope Geochemistry Model



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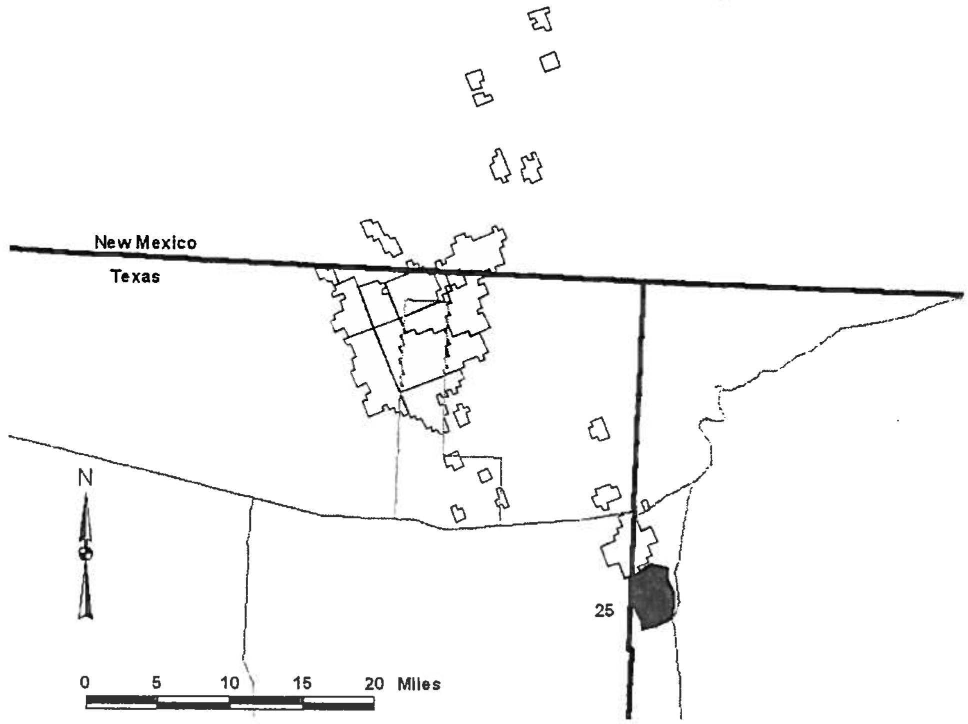
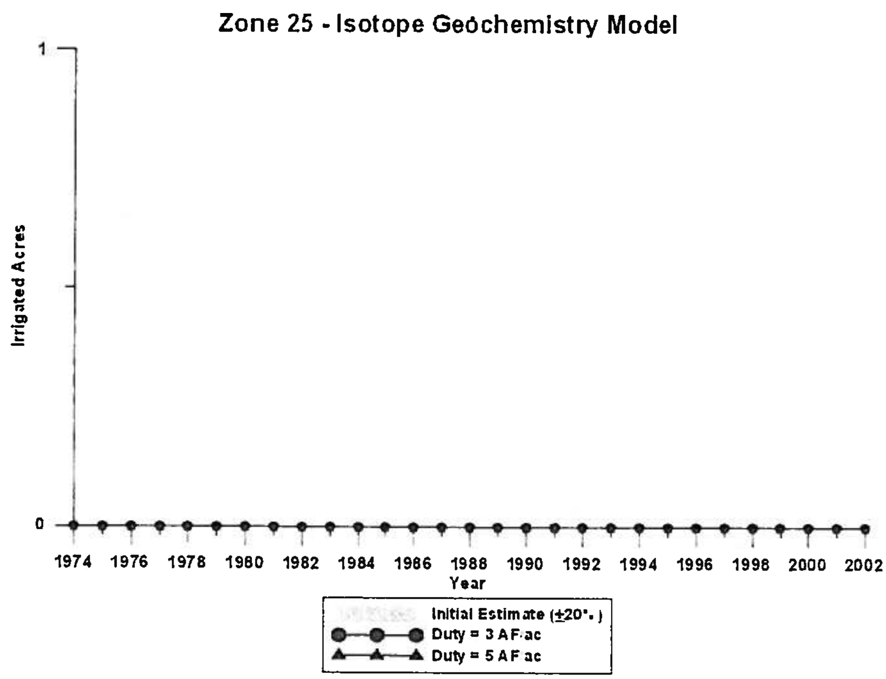
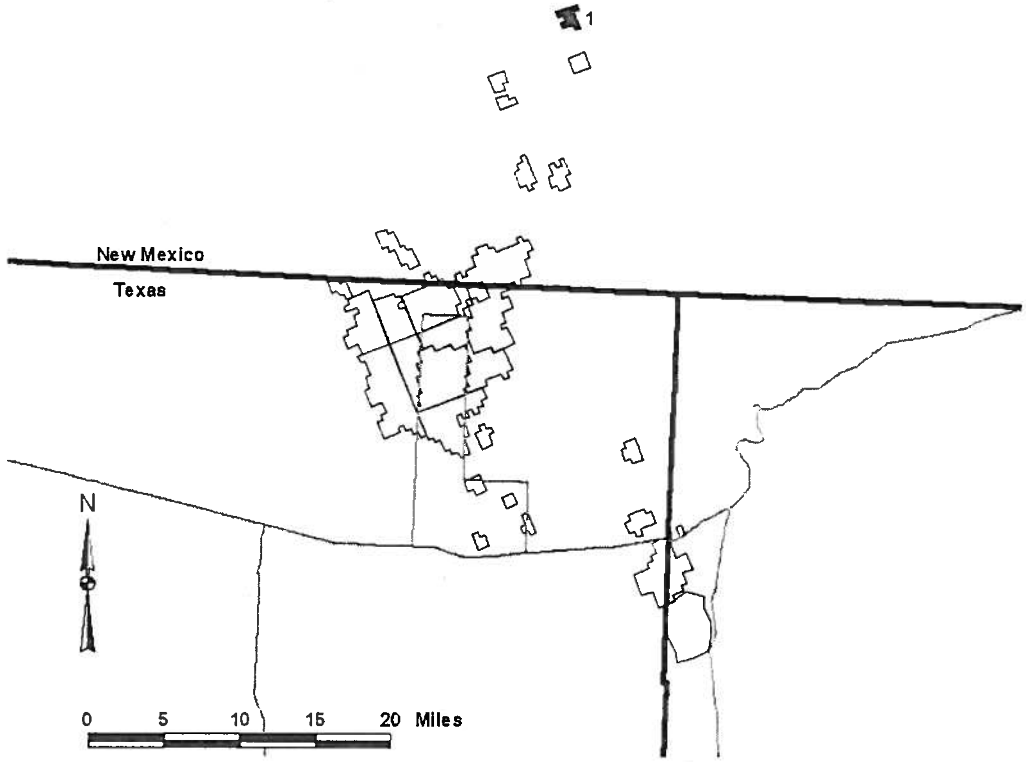


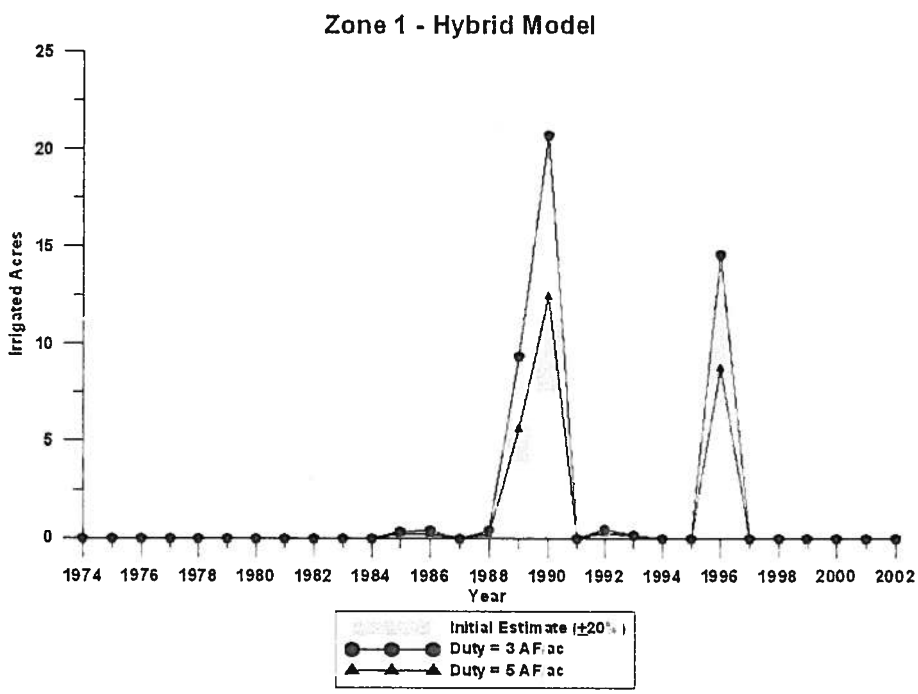


Note: Initial Estimate Range from Groeneveld and Baugh (2002)

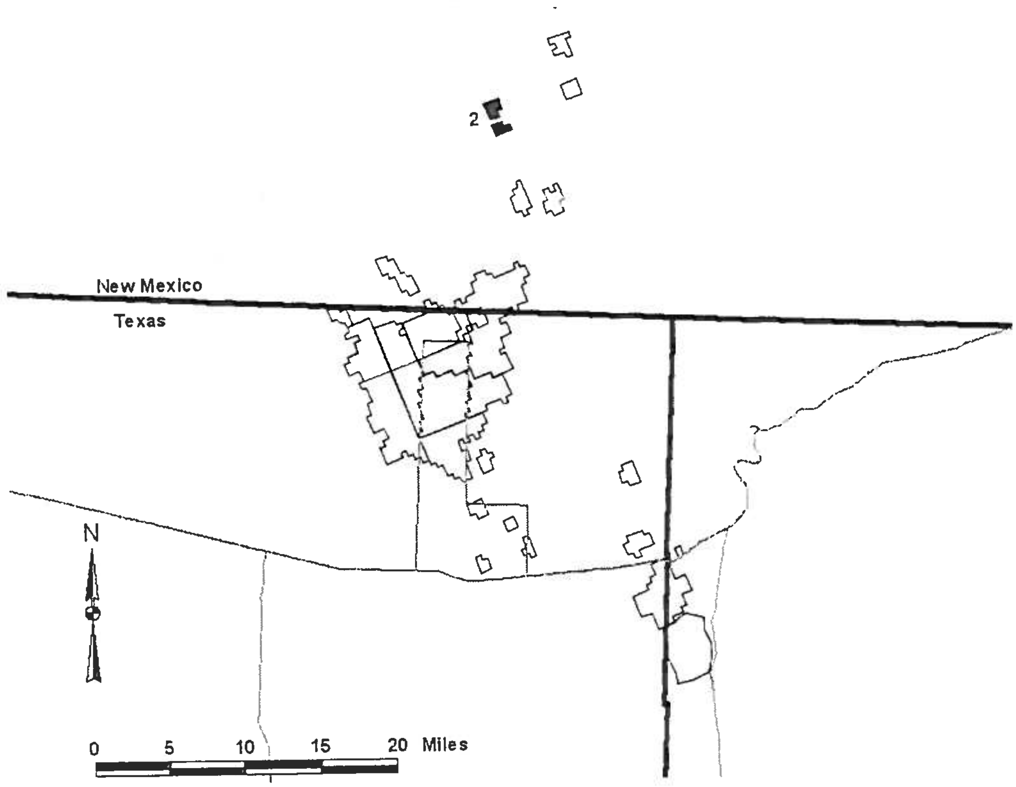
Appendix B-3

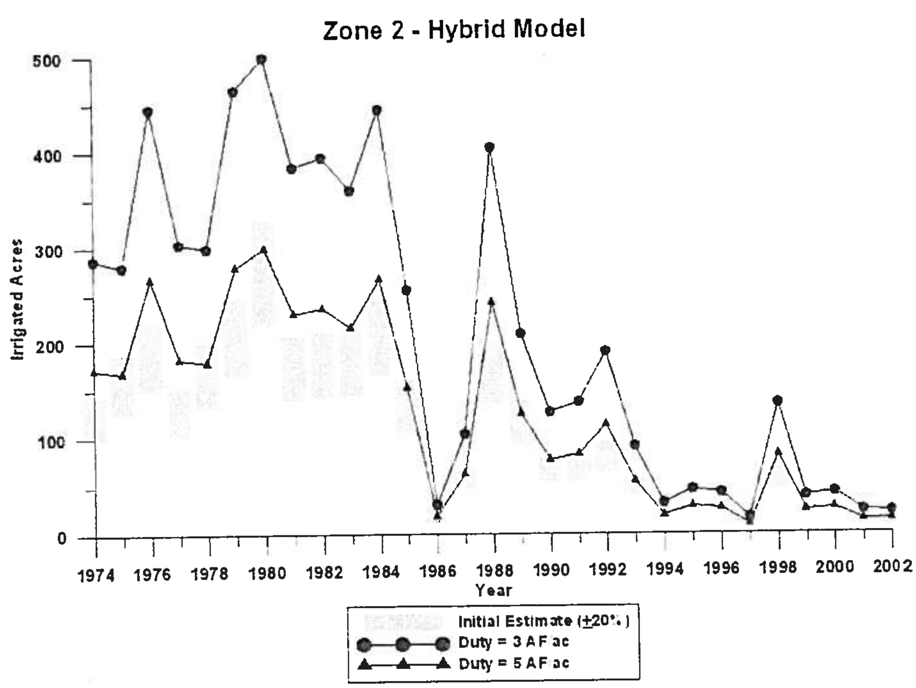
Irrigated Acreage Estimates for Each Pumping Zone
Hybrid Model





Note: Initial Estimate Range from Groeneveld and Baugh (2002)





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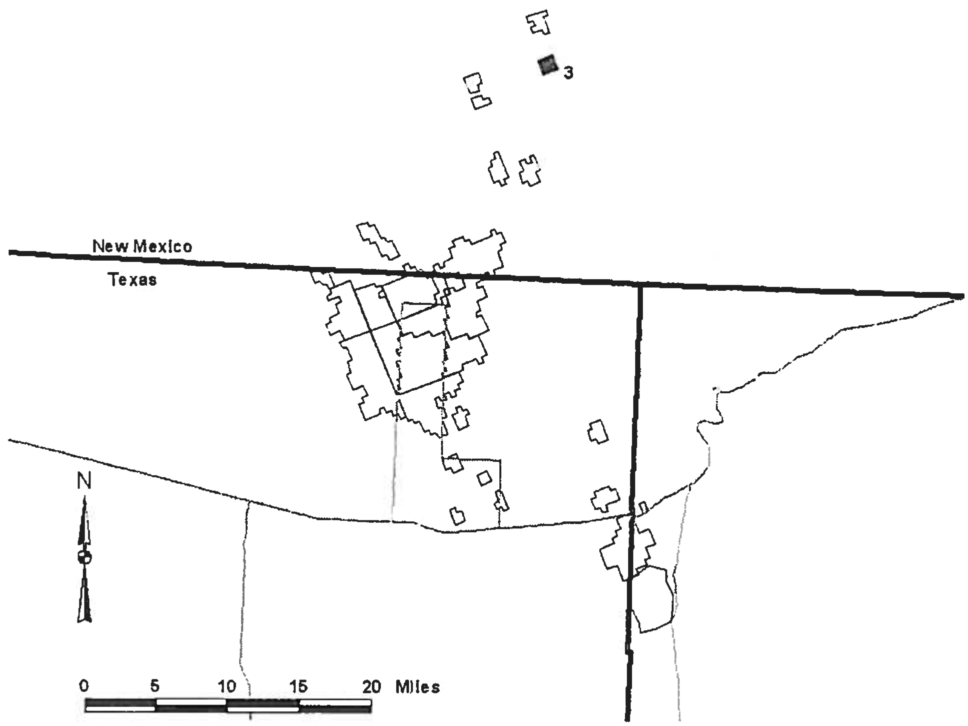
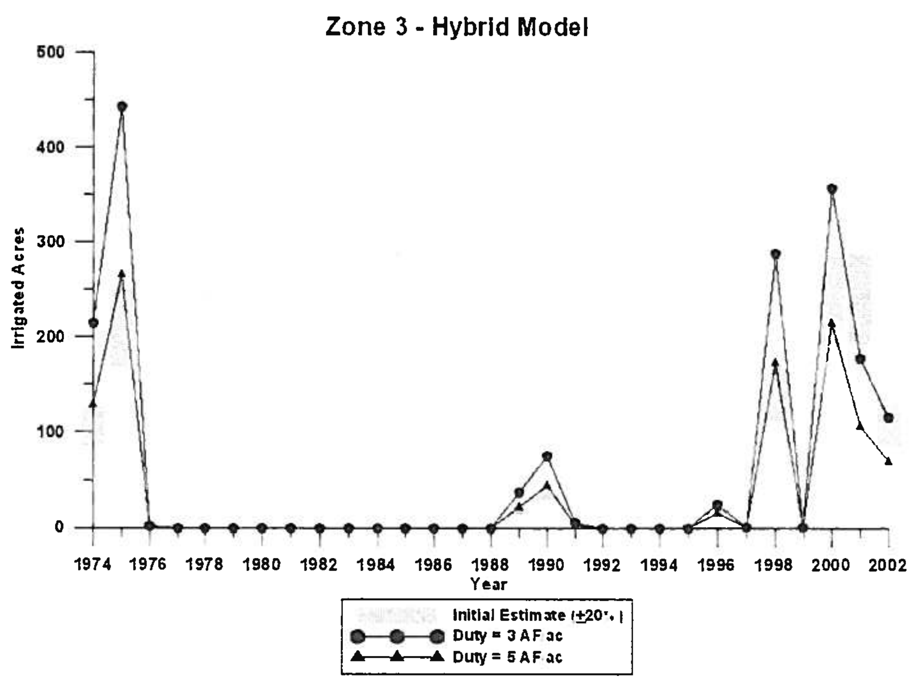
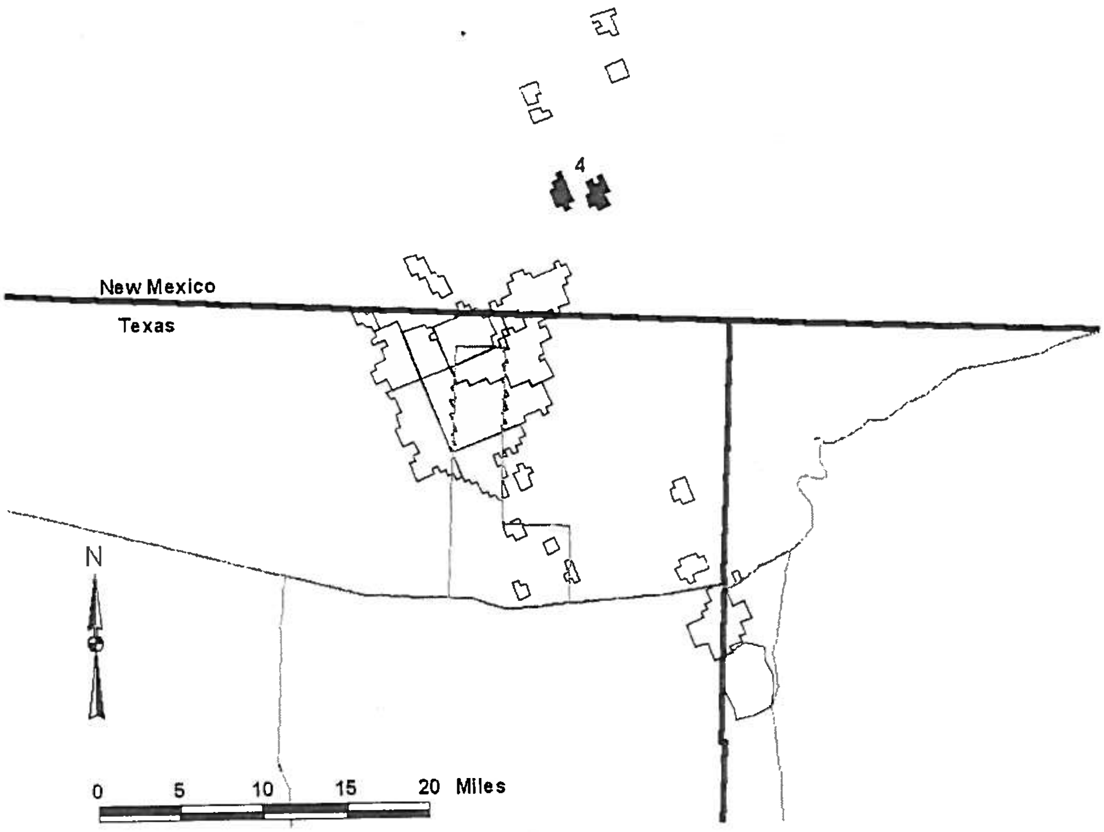
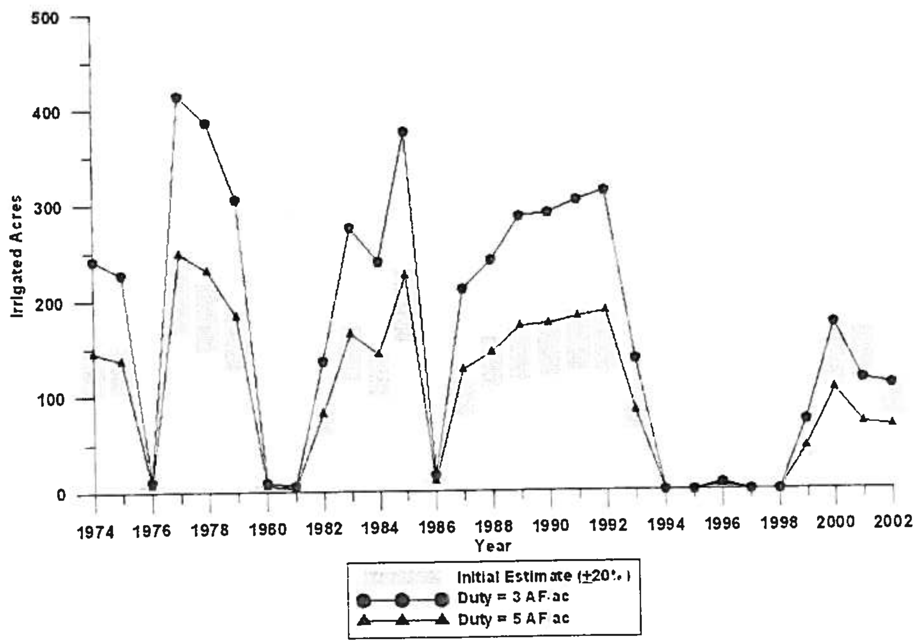




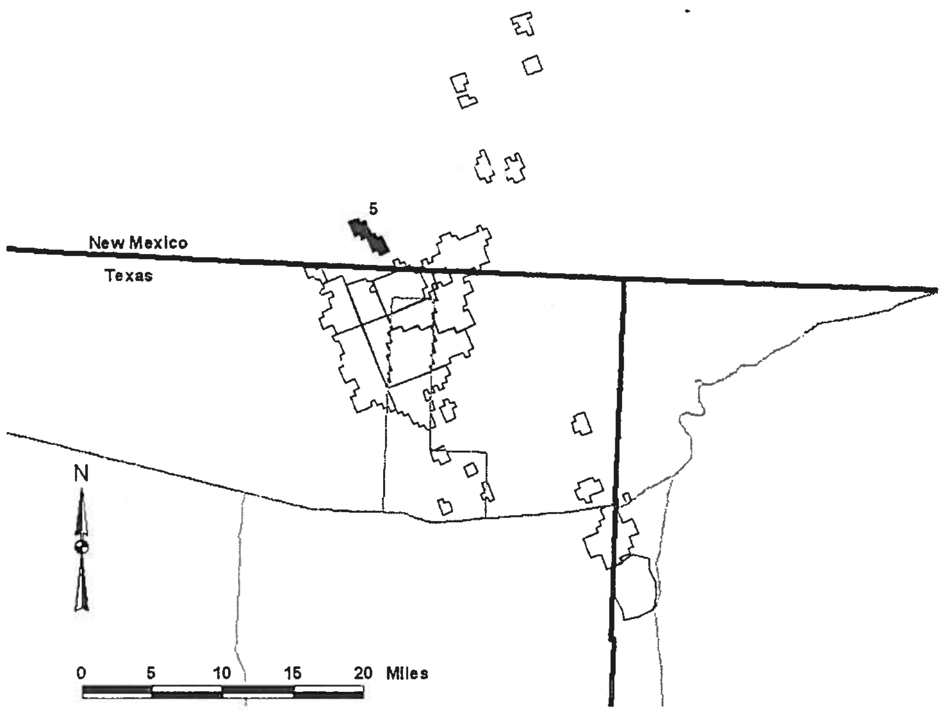
Note: Initial Estimate Range from Groeneveld and Baugh (2002)

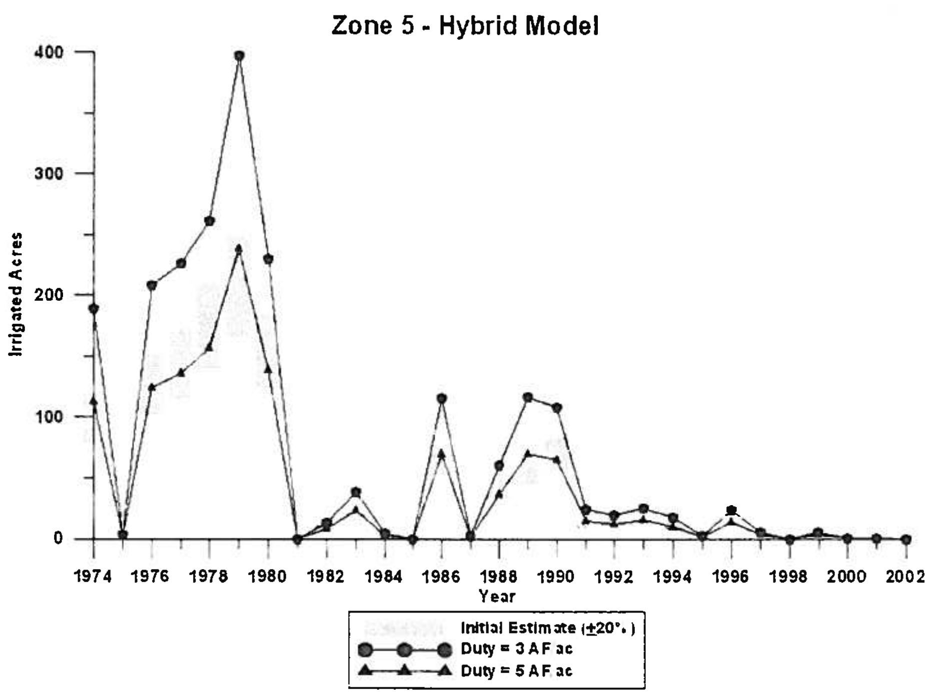


Zone 4 - Hybrid Model



Note: Initial Estimate Range from Groeneveld and Baugh (2002)





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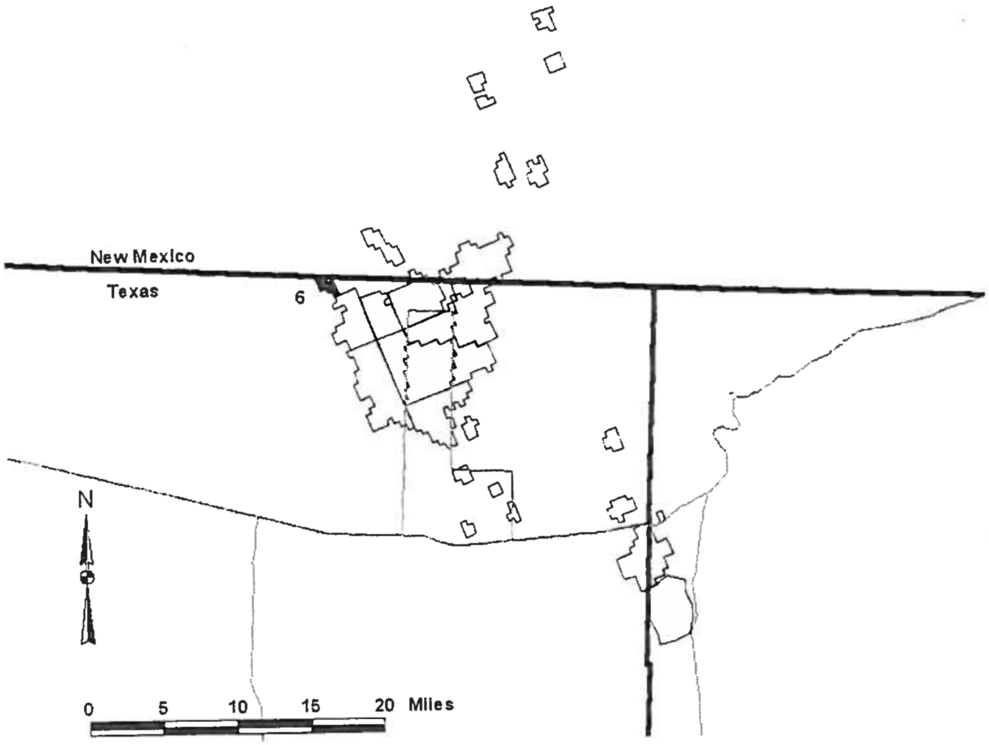

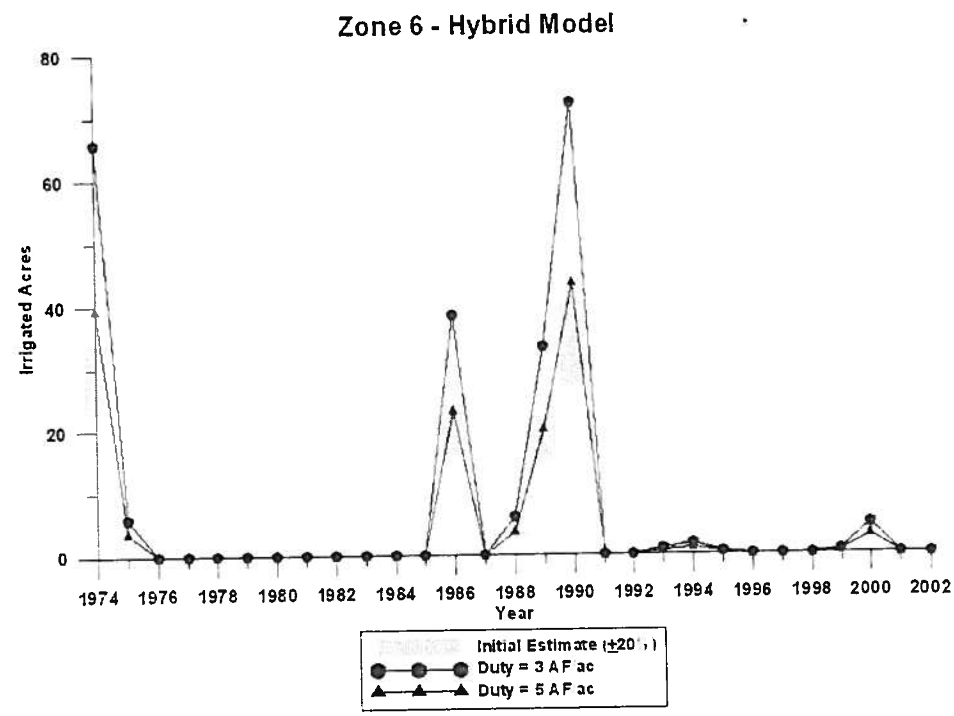

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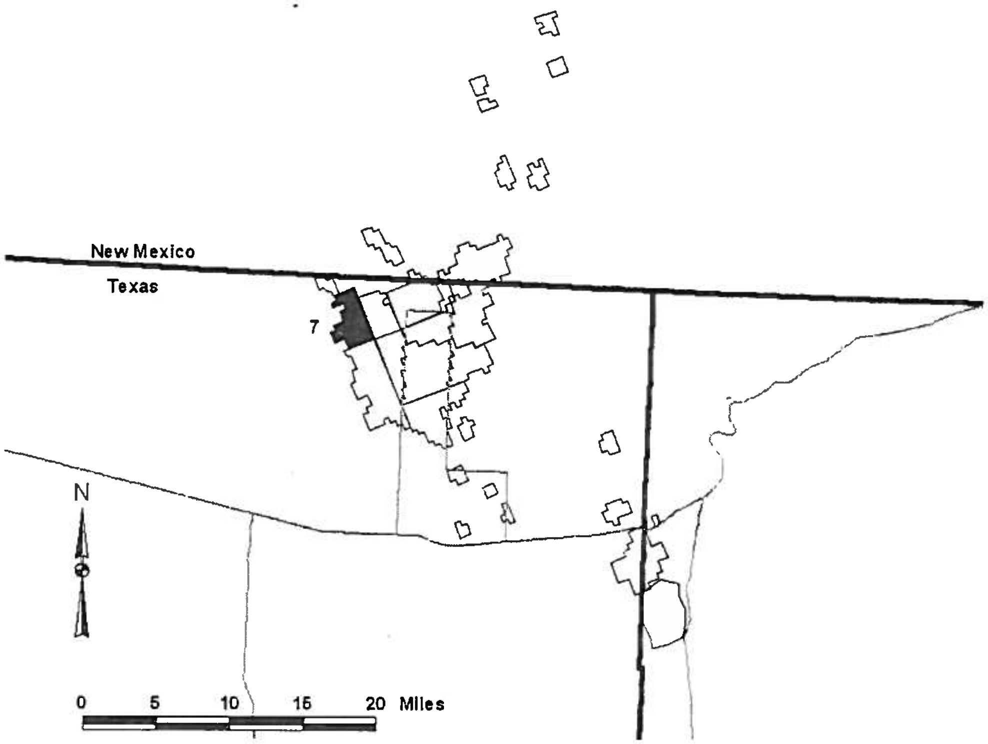
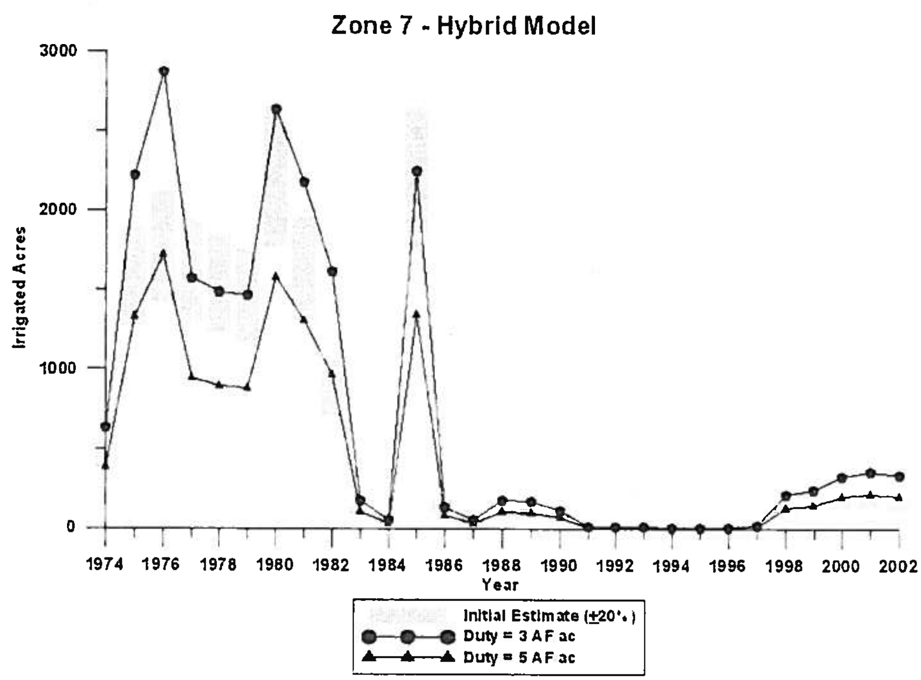
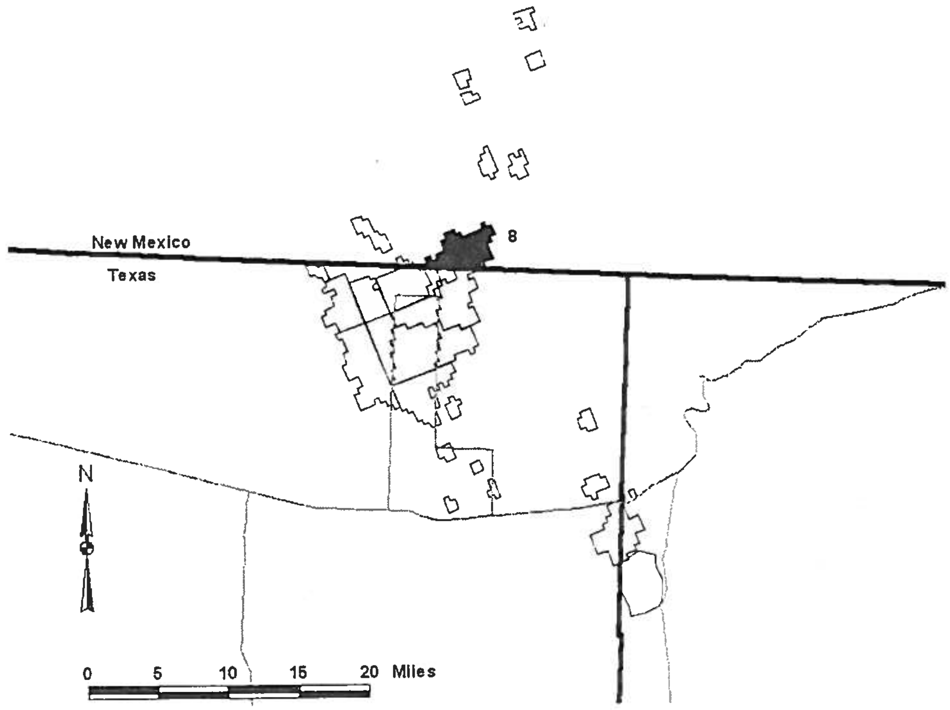
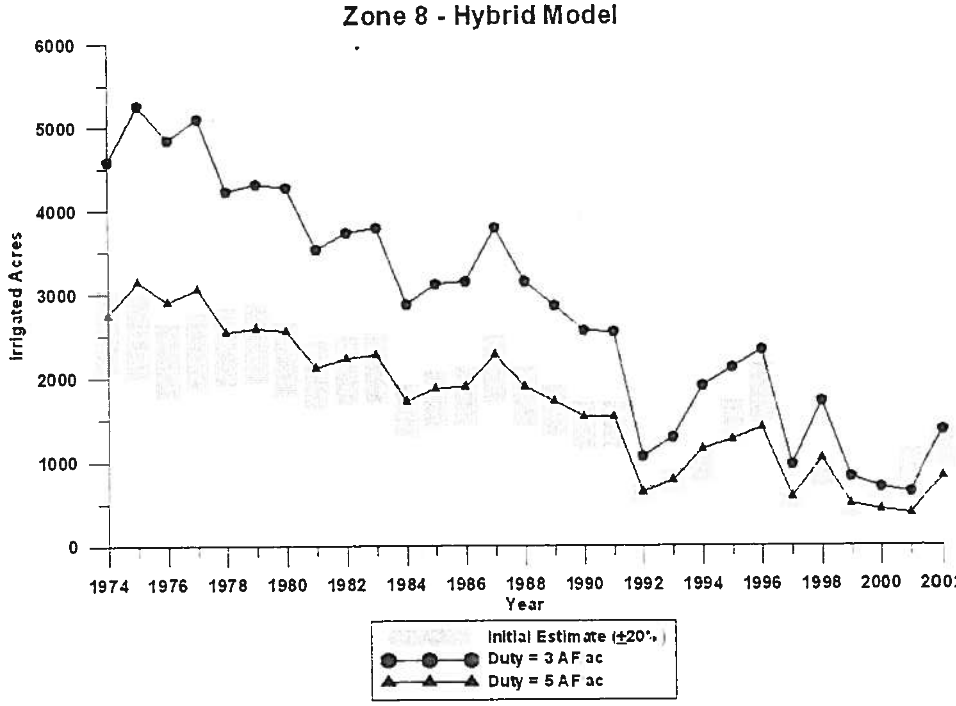




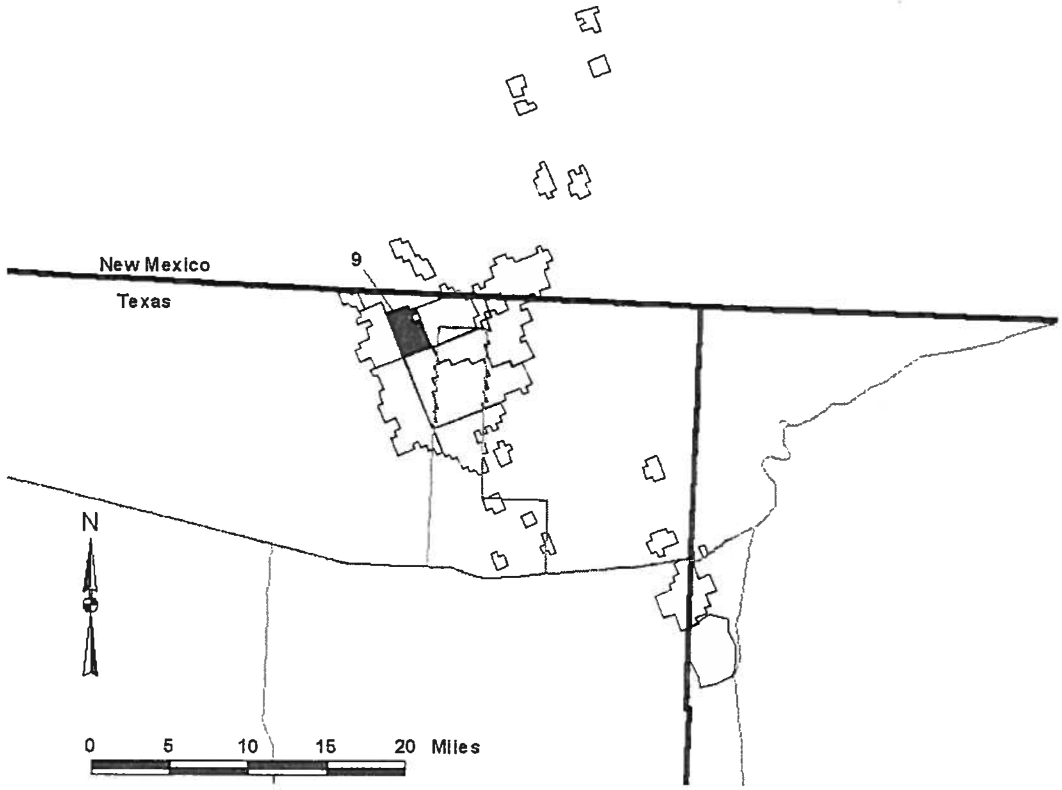
Note: Initial Estimate Range from Groeneveld and Baugh (2002)



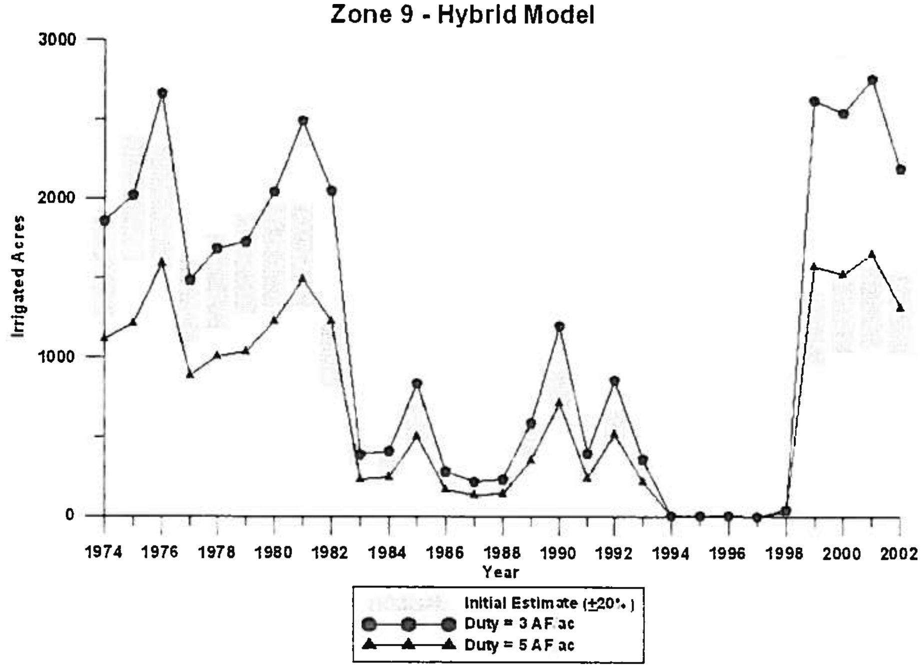
Zone 8 - Hybrid Model



Note: Initial Estimate Range from Groeneveld and Baugh (2002)



Zone 9 - Hybrid Model



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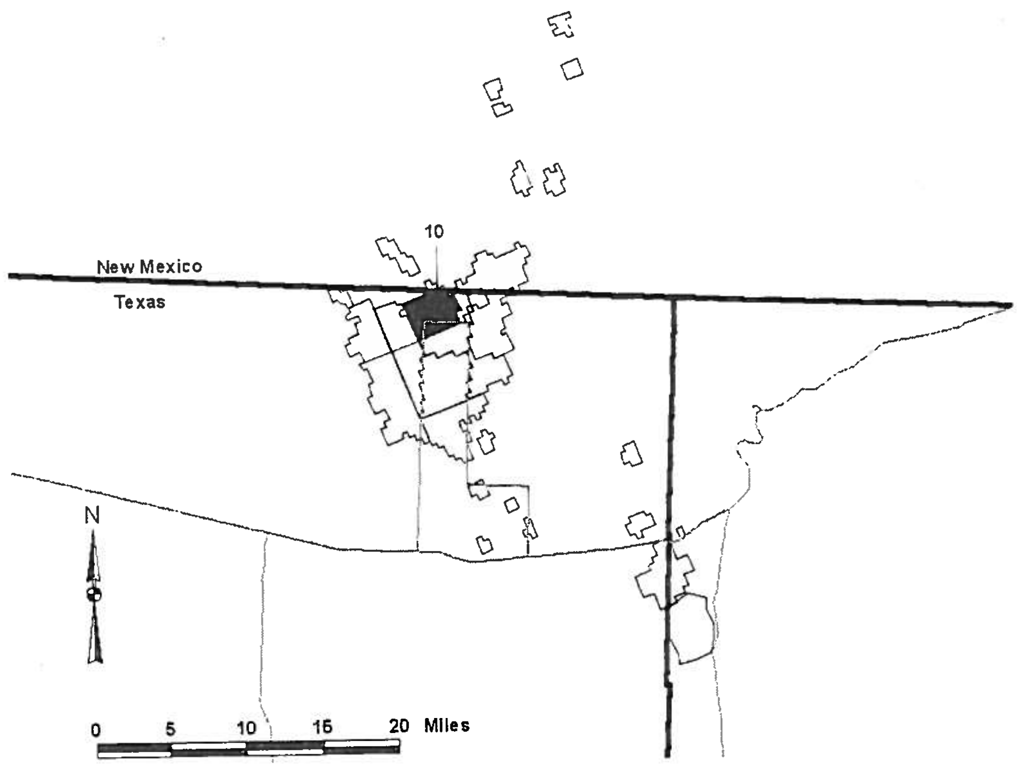

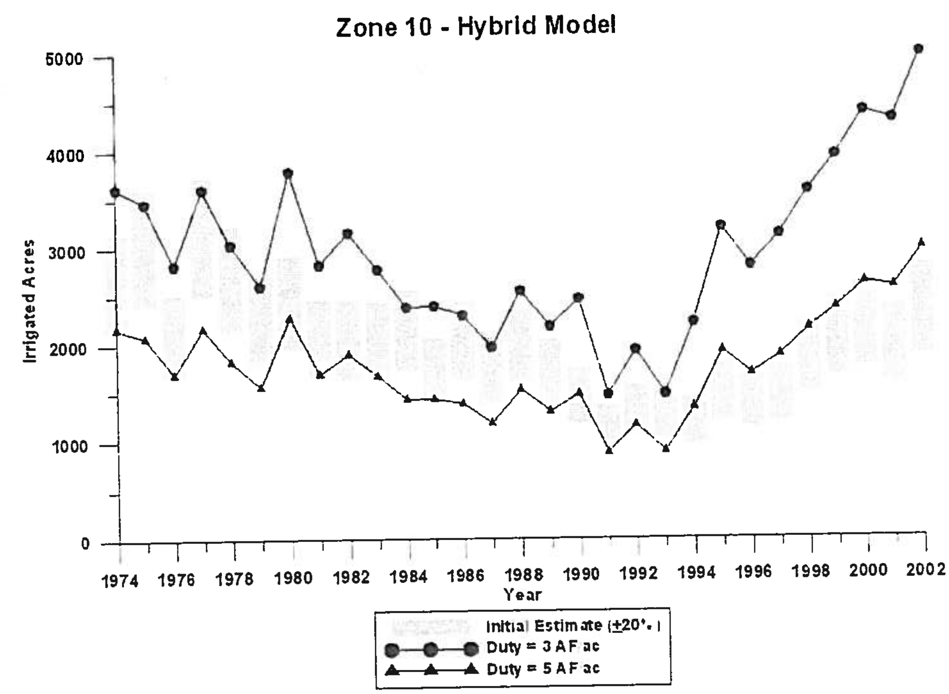

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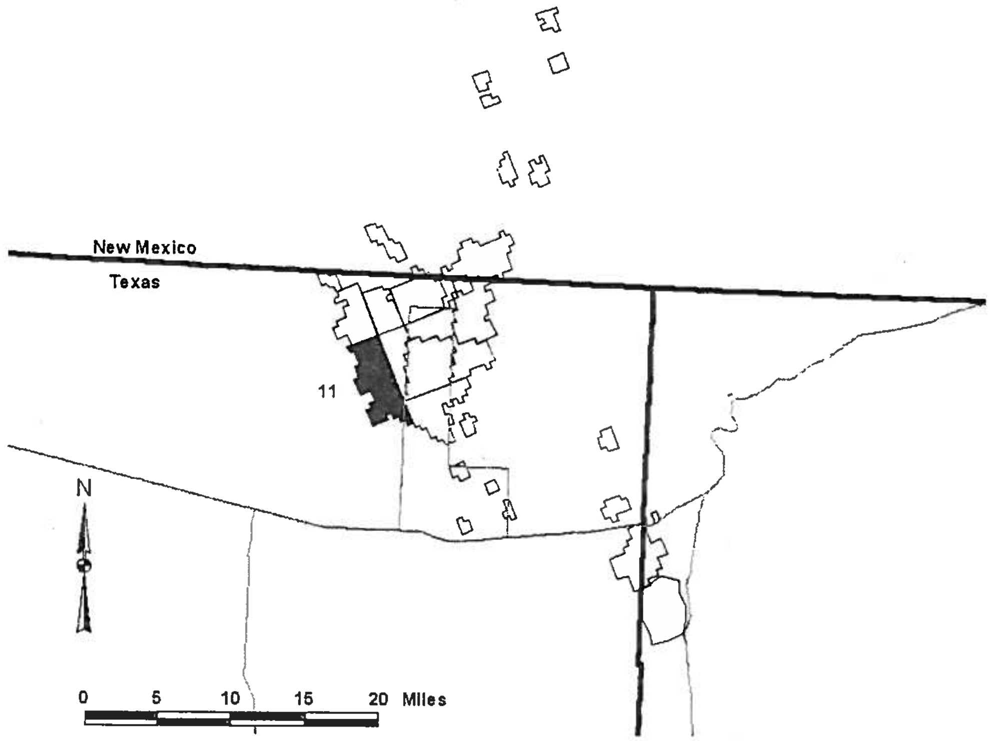
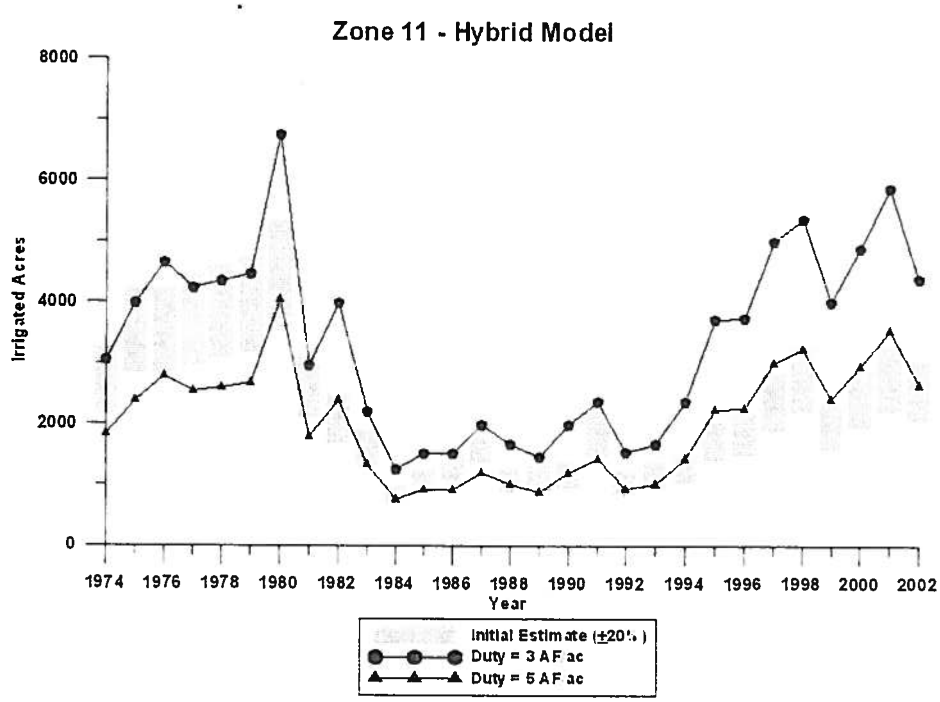
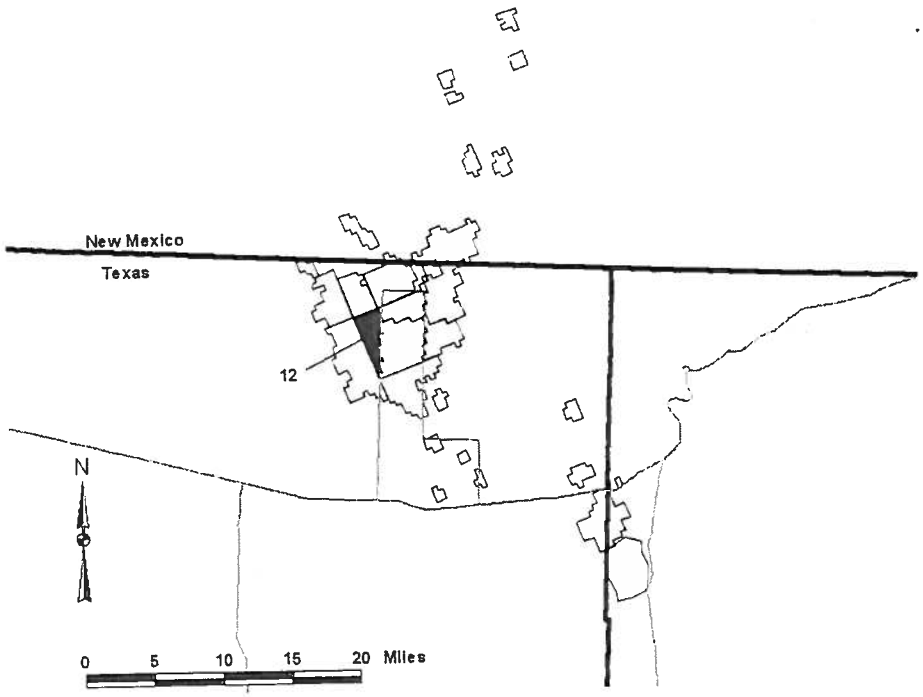
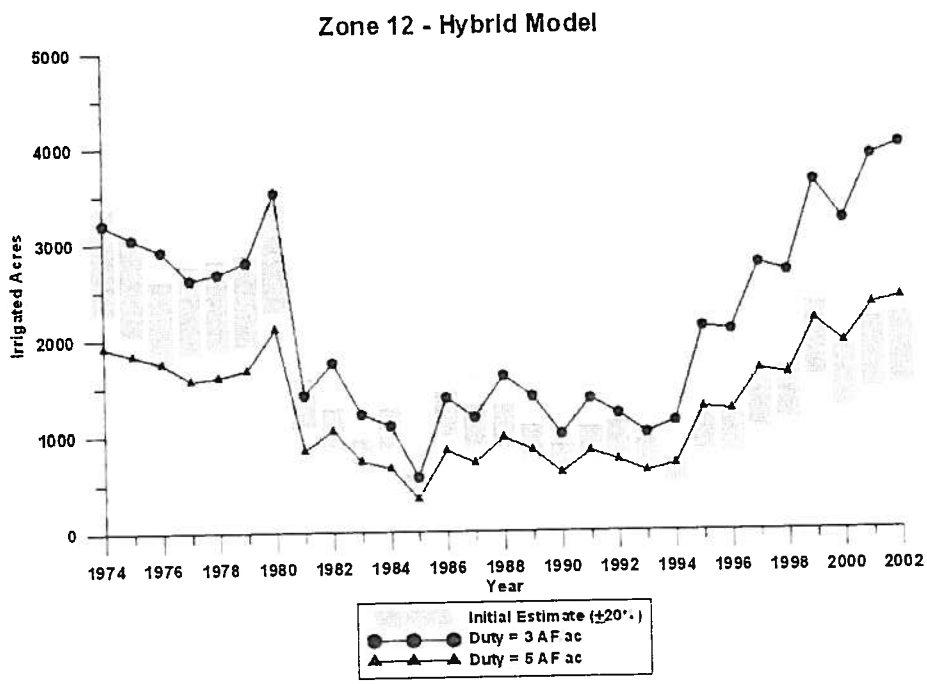




Note: Initial Estimate Range from Groeneveld and Baugh (2002)





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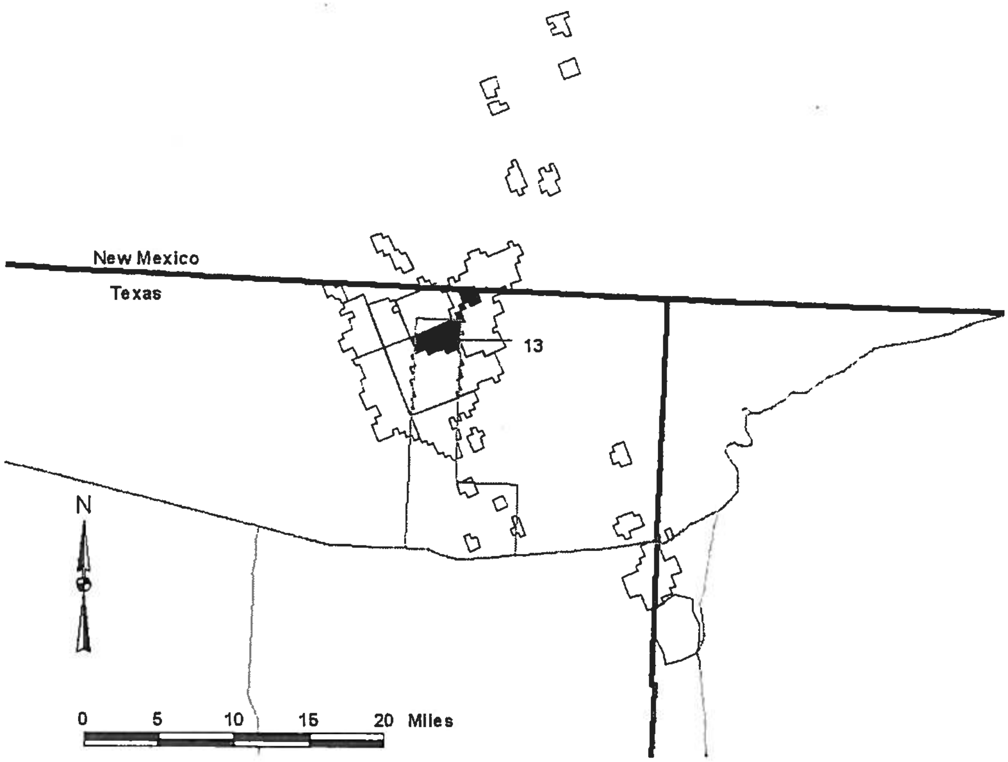

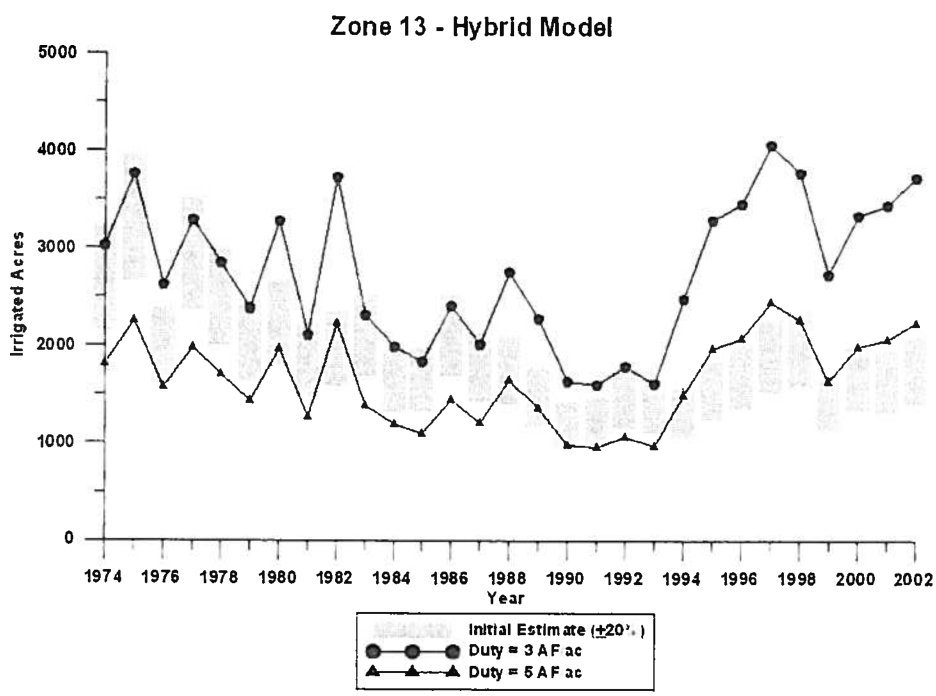

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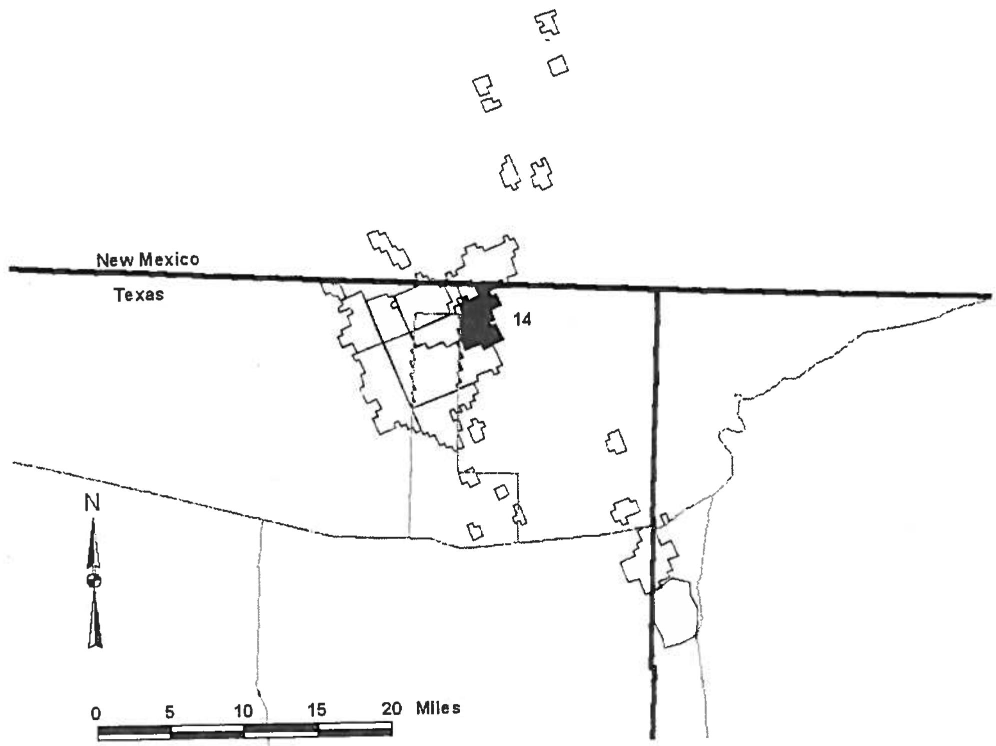

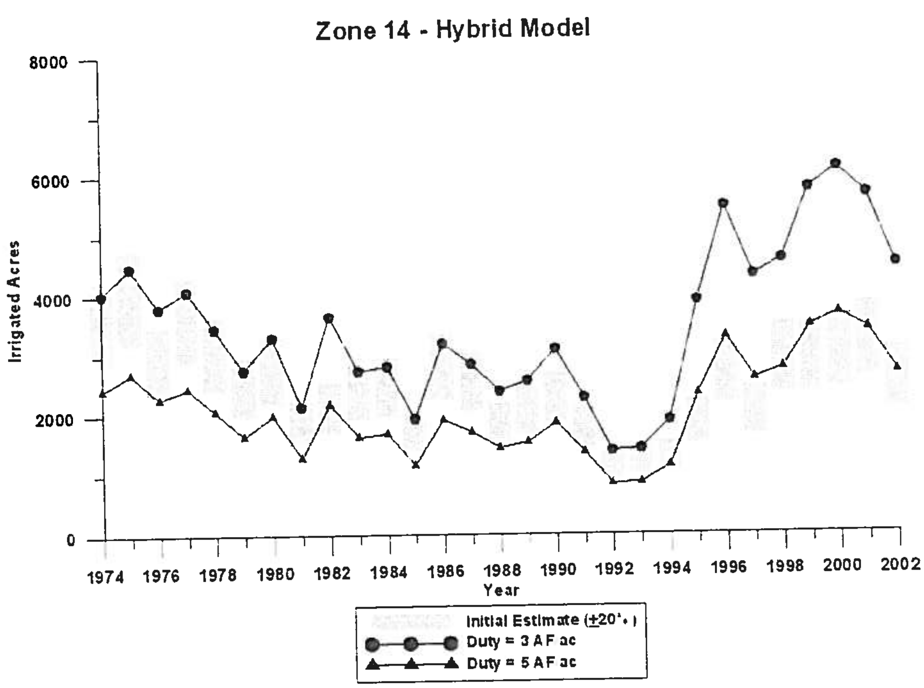

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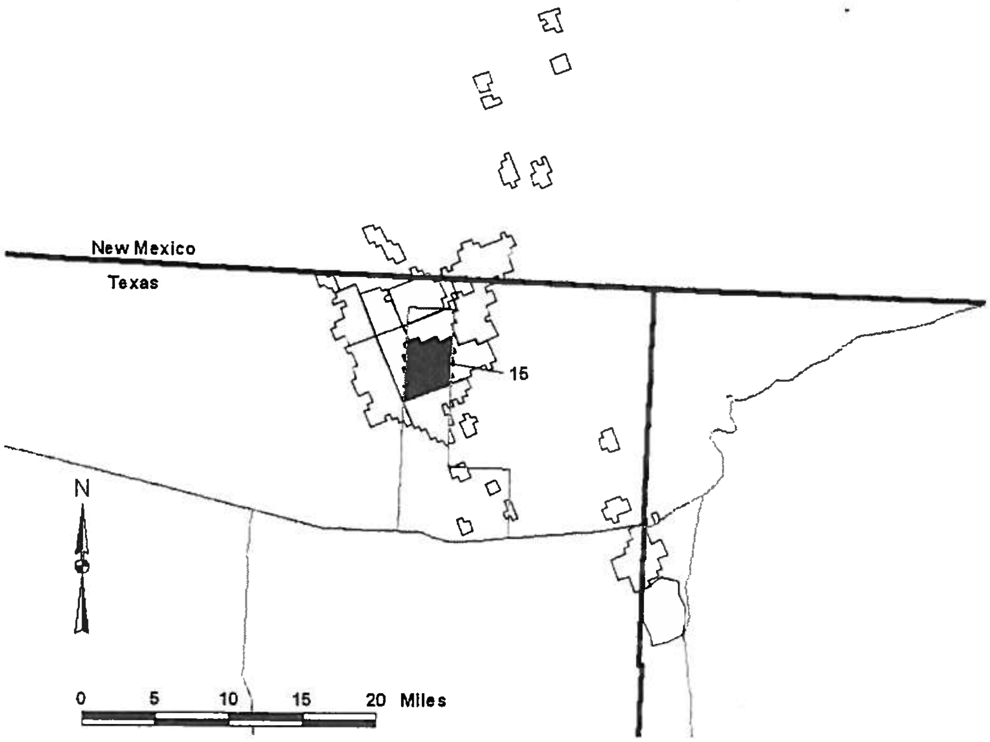

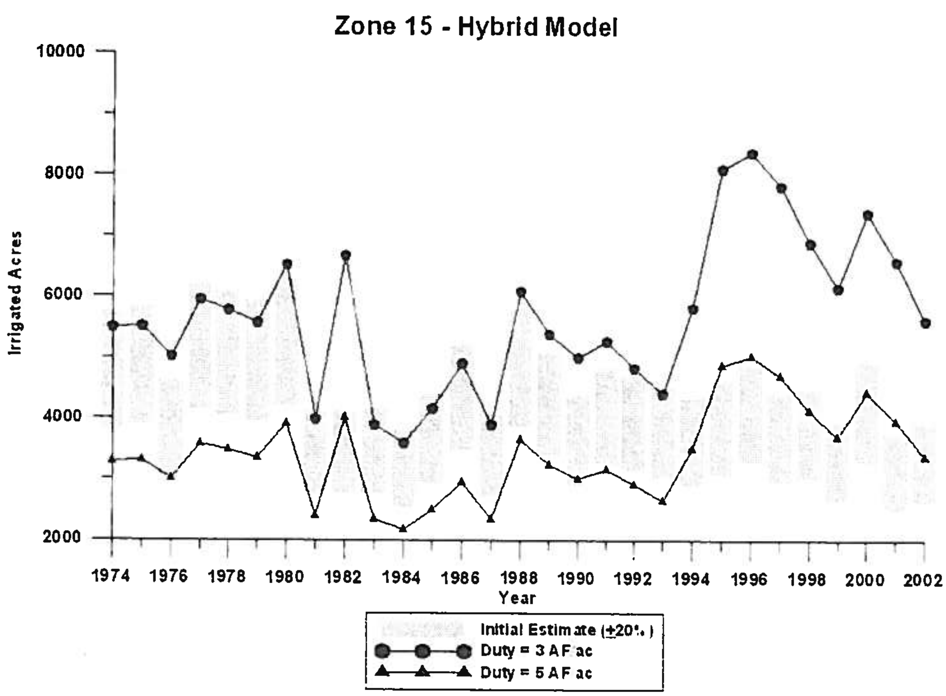

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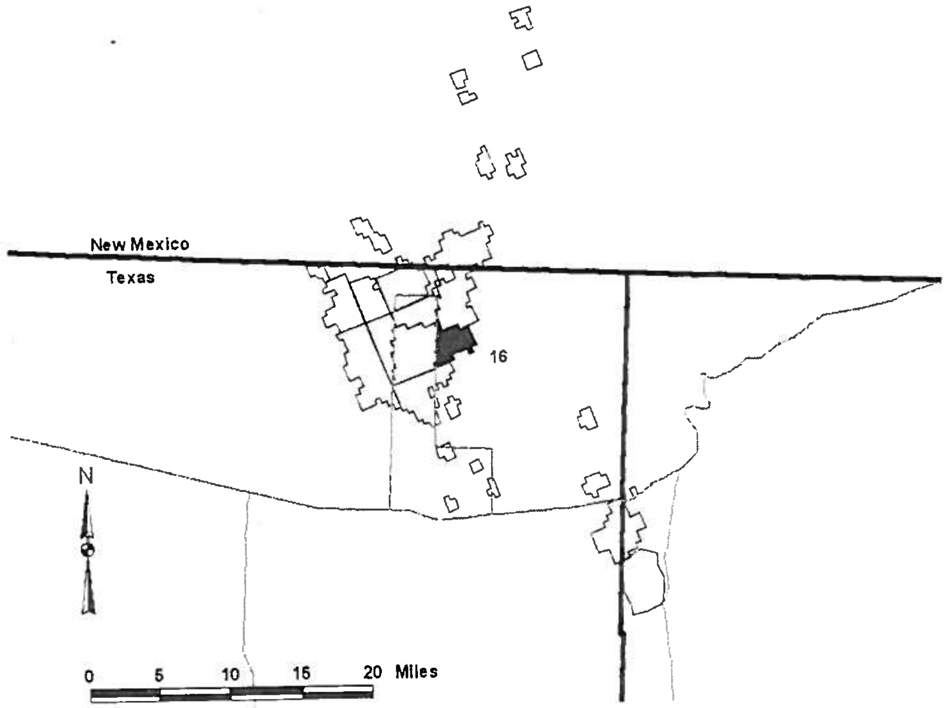

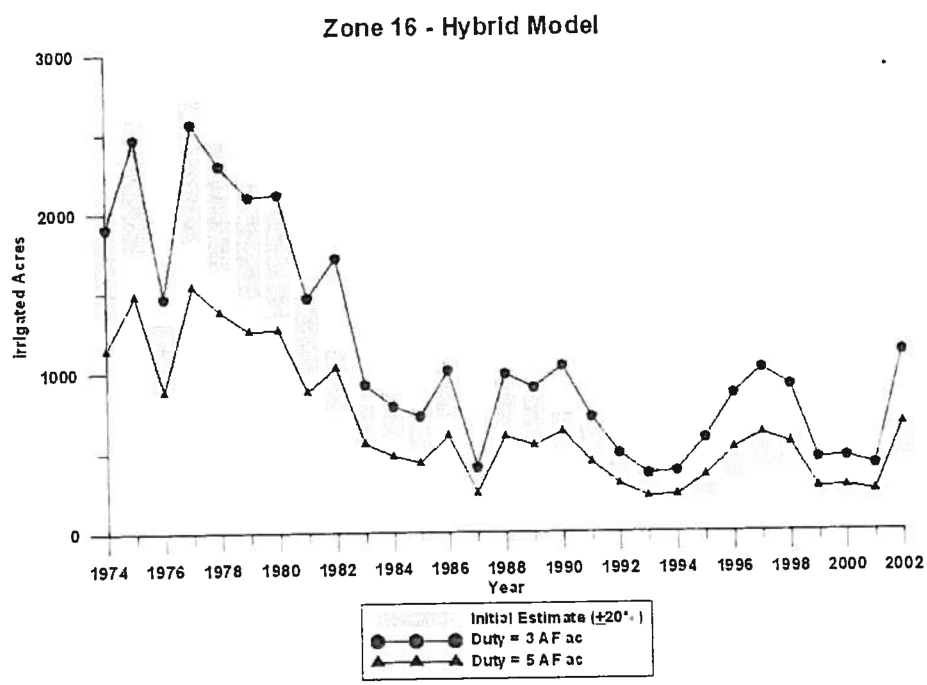

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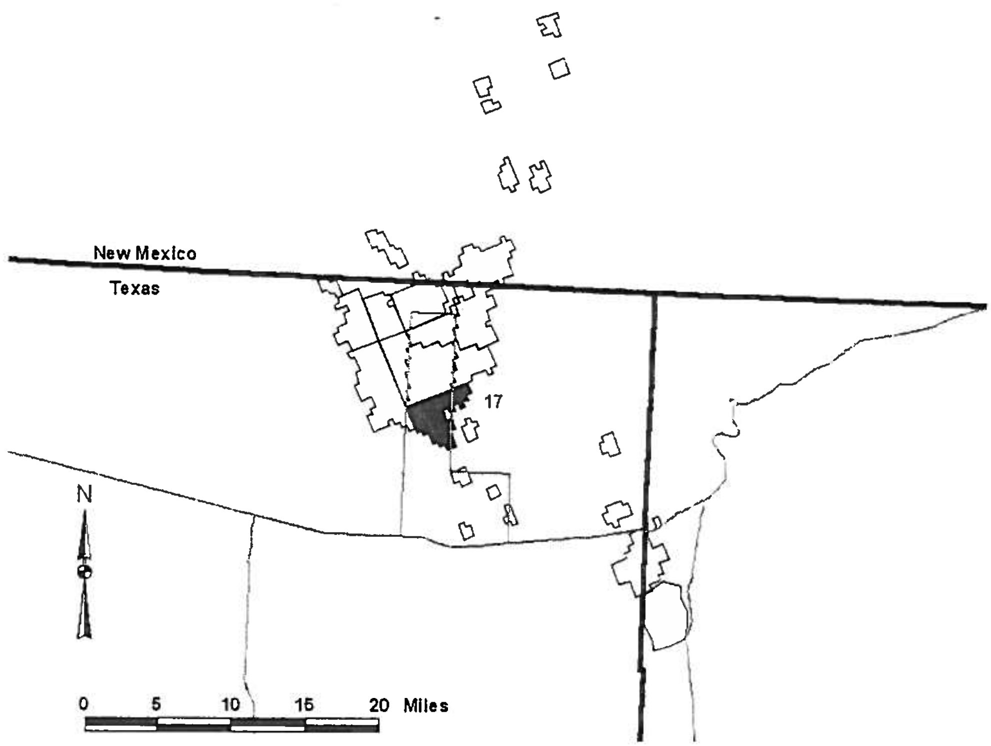

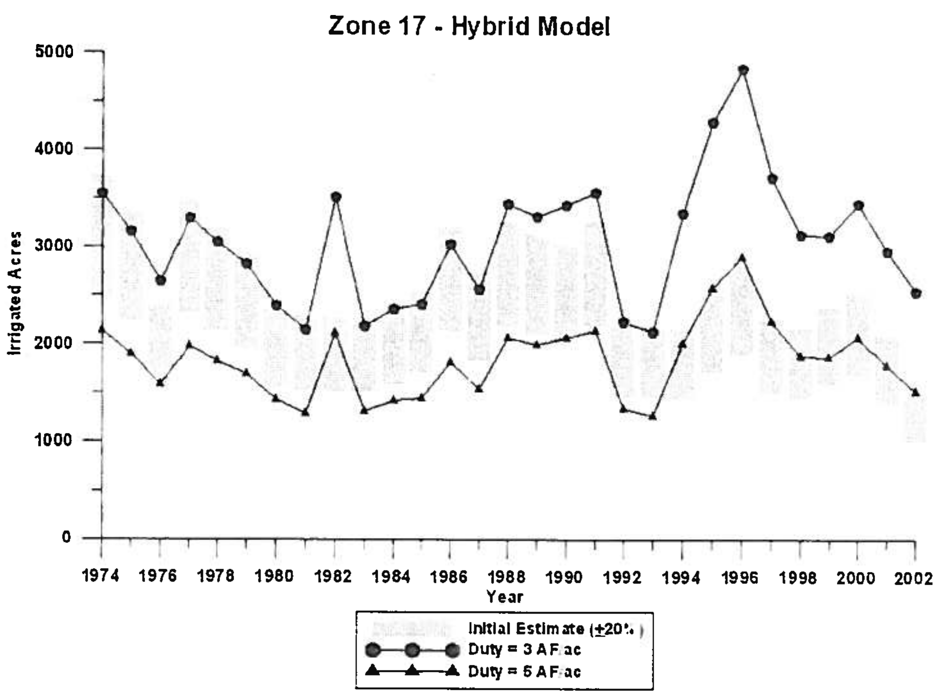

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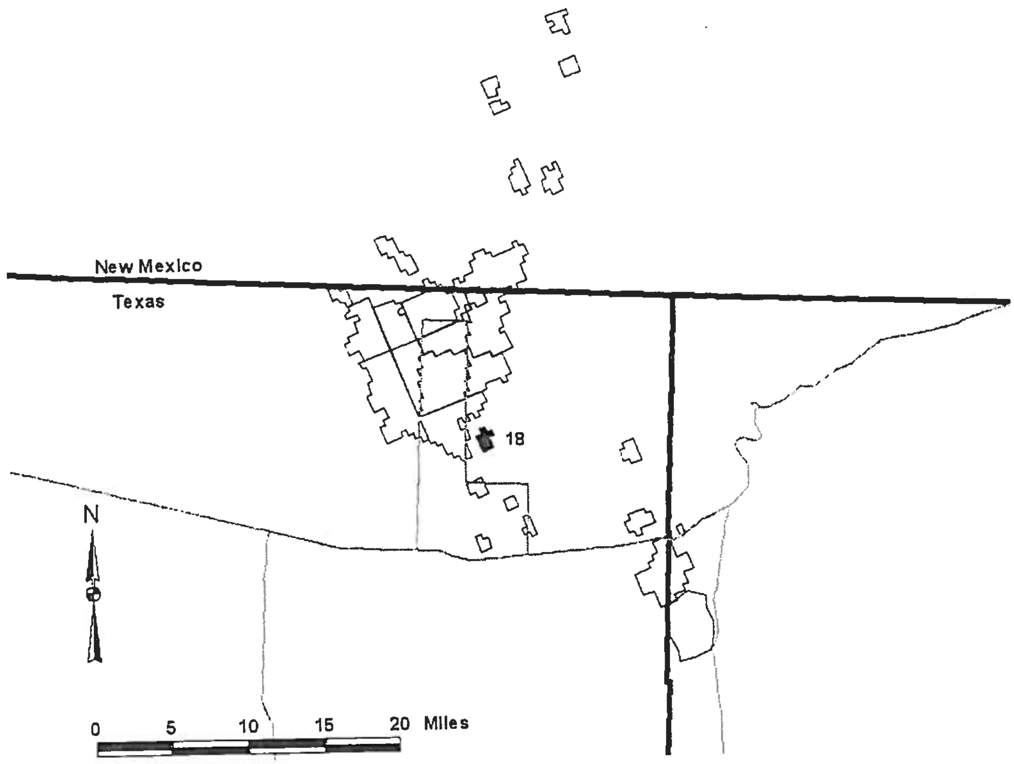

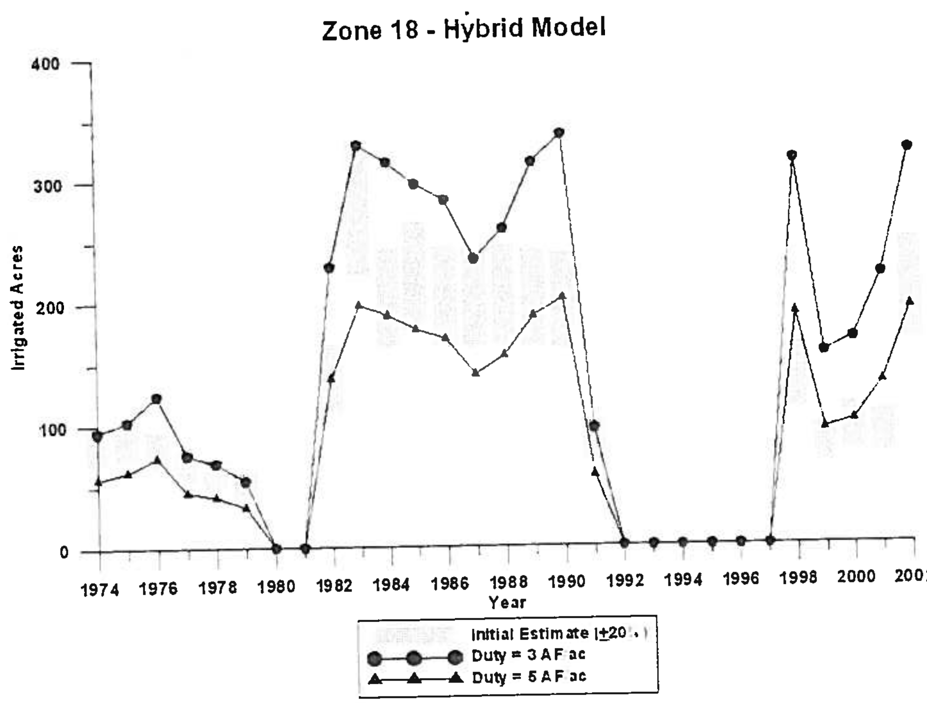

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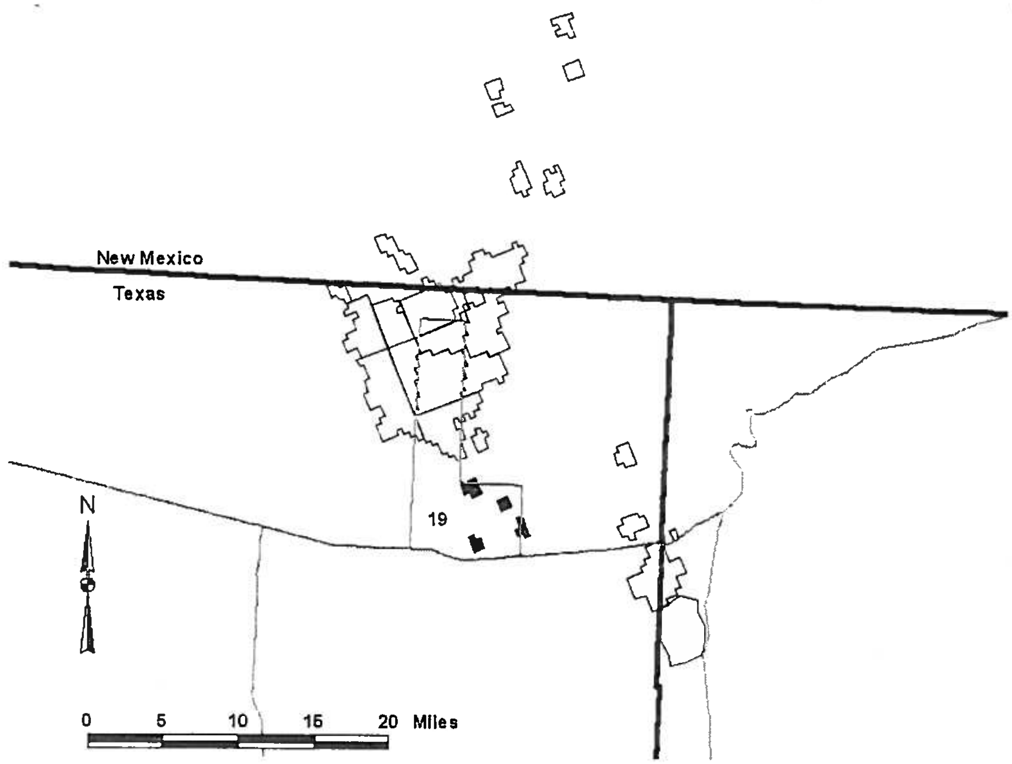

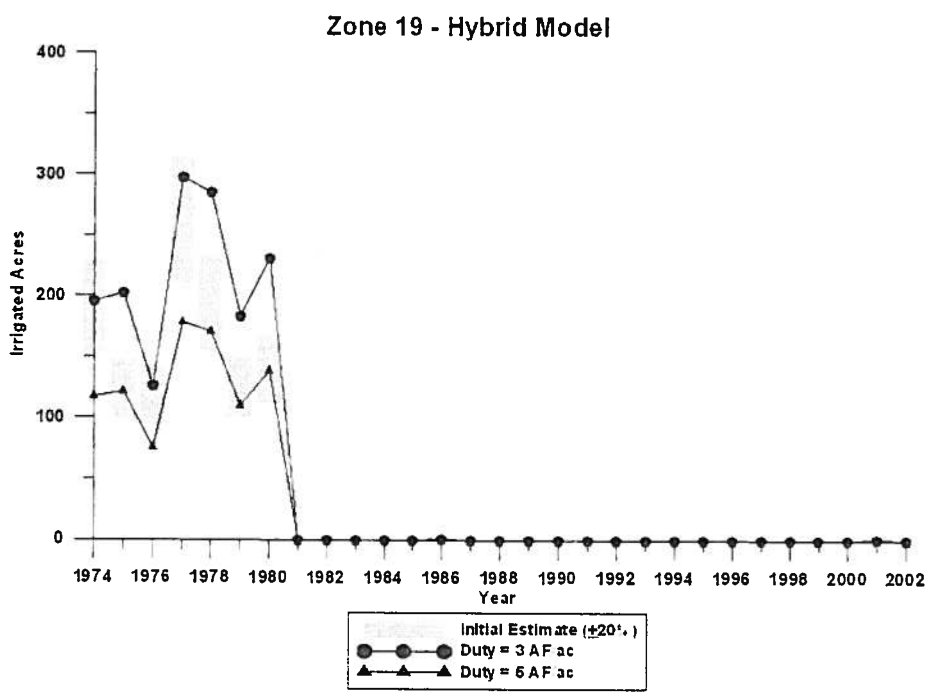

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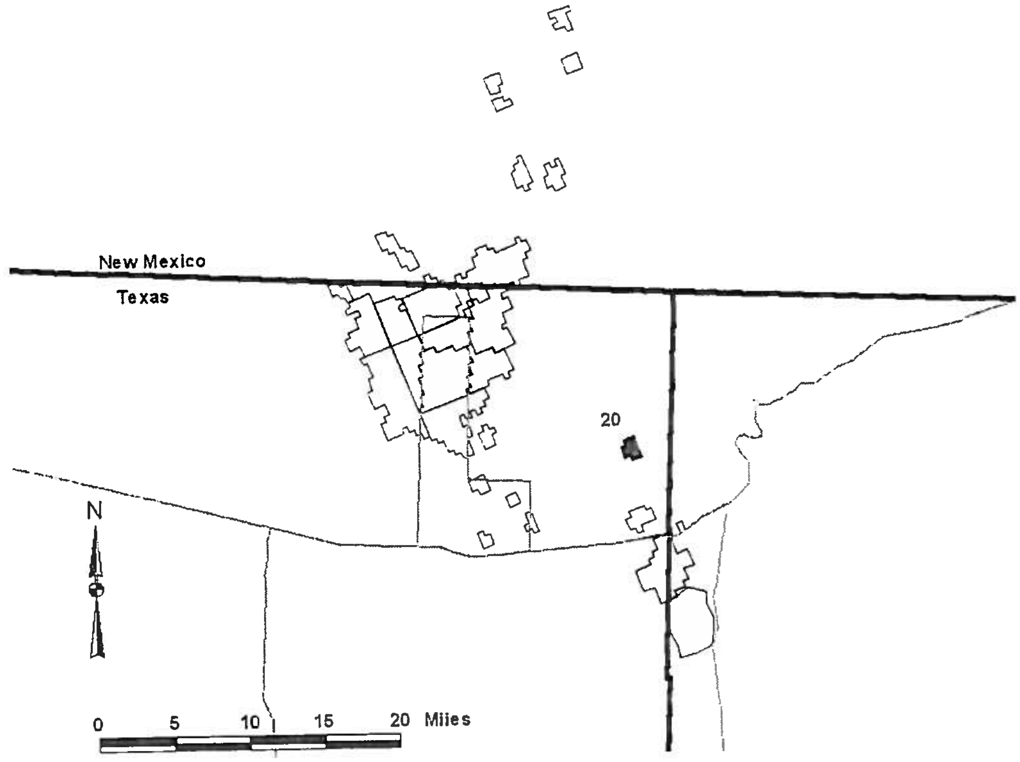

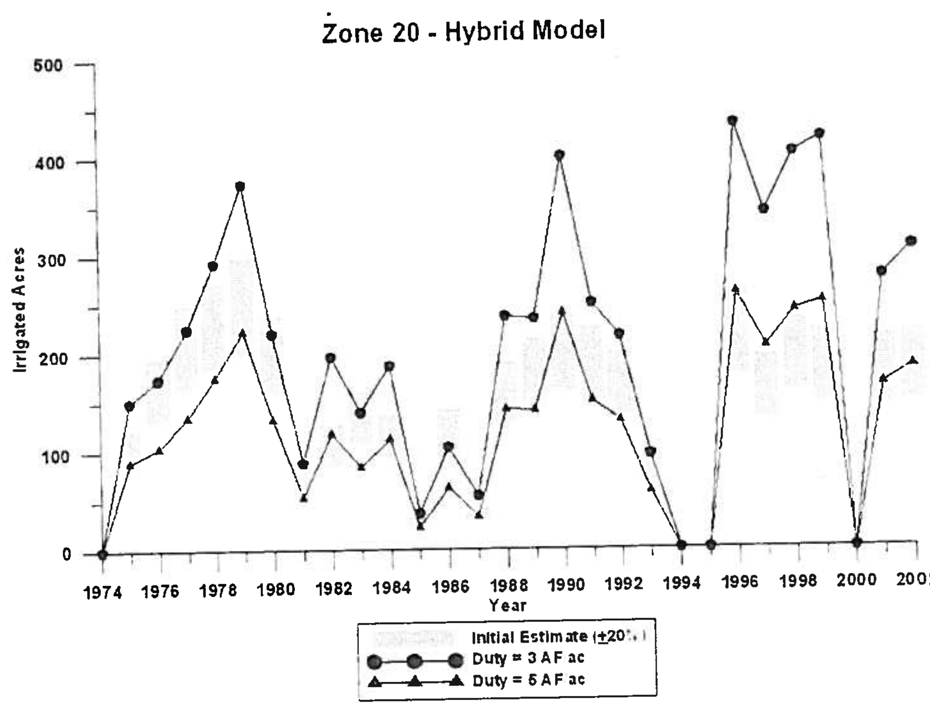

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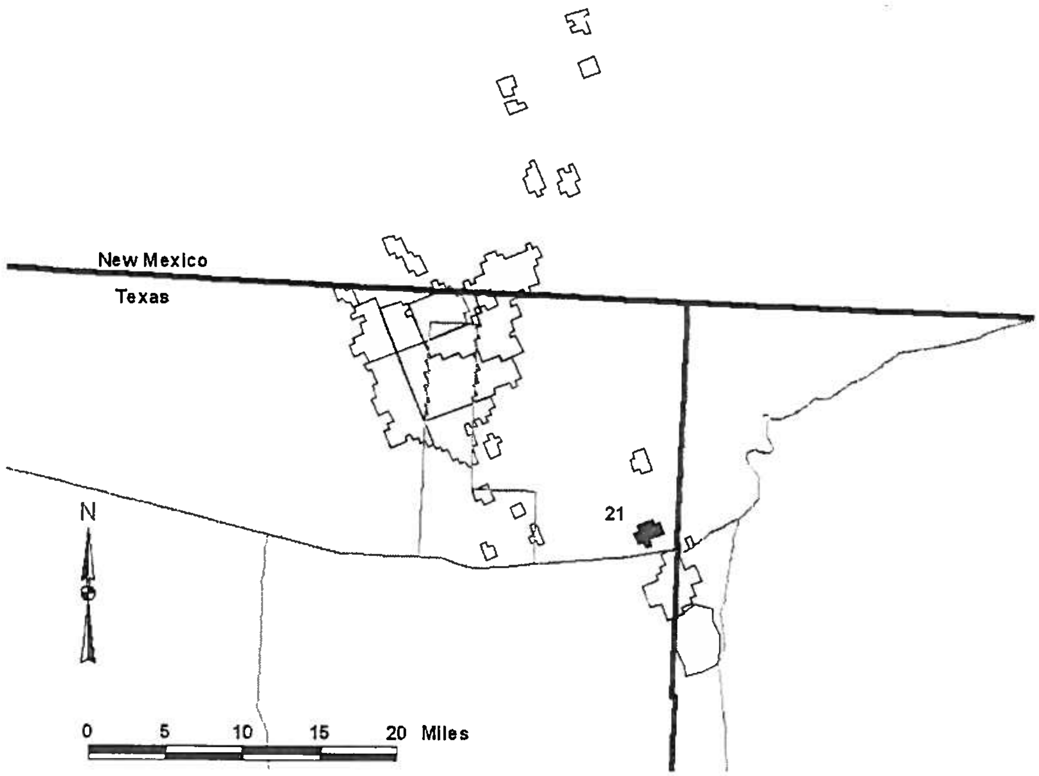

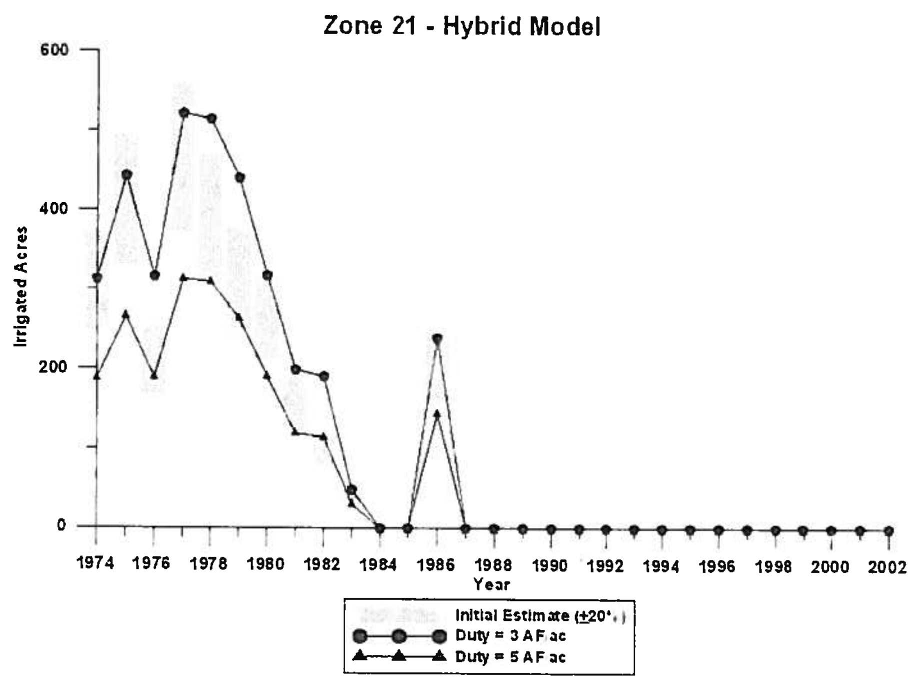

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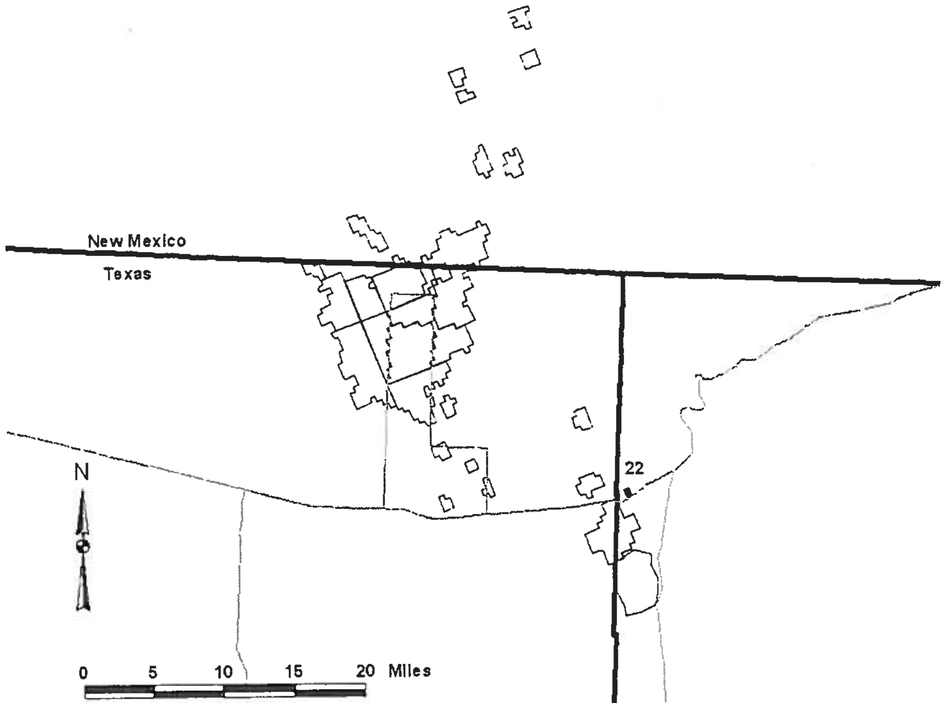

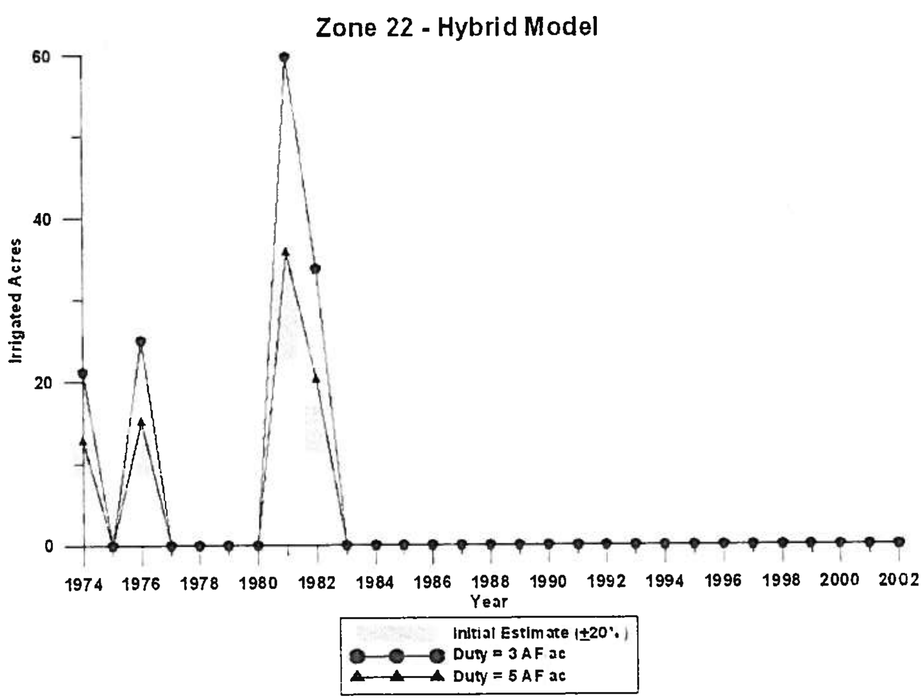

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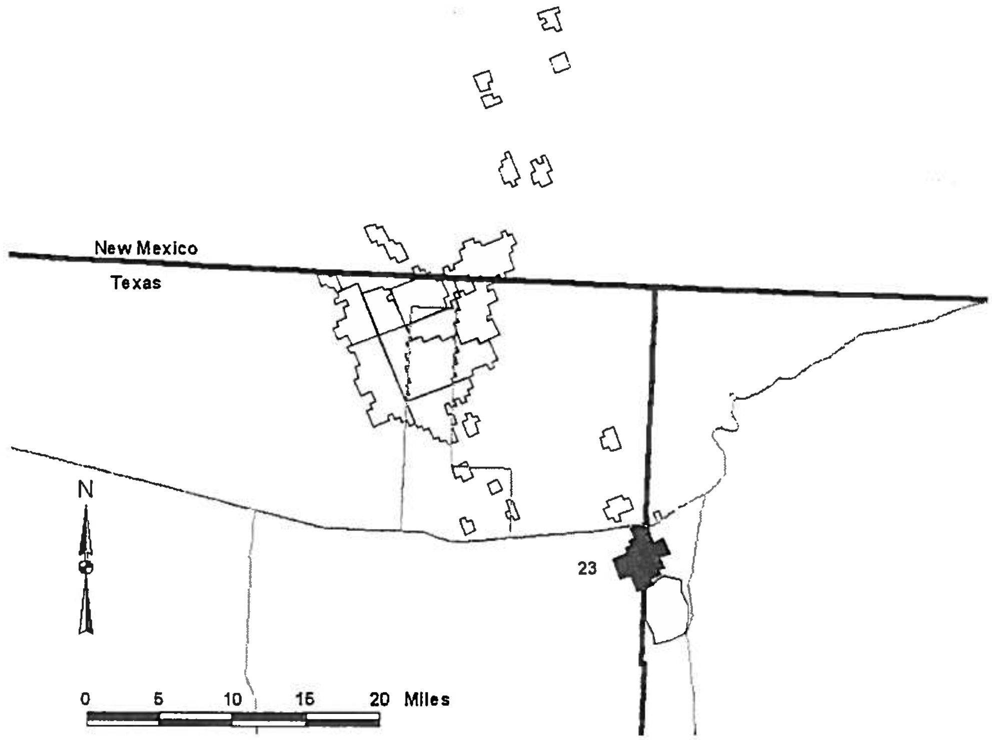

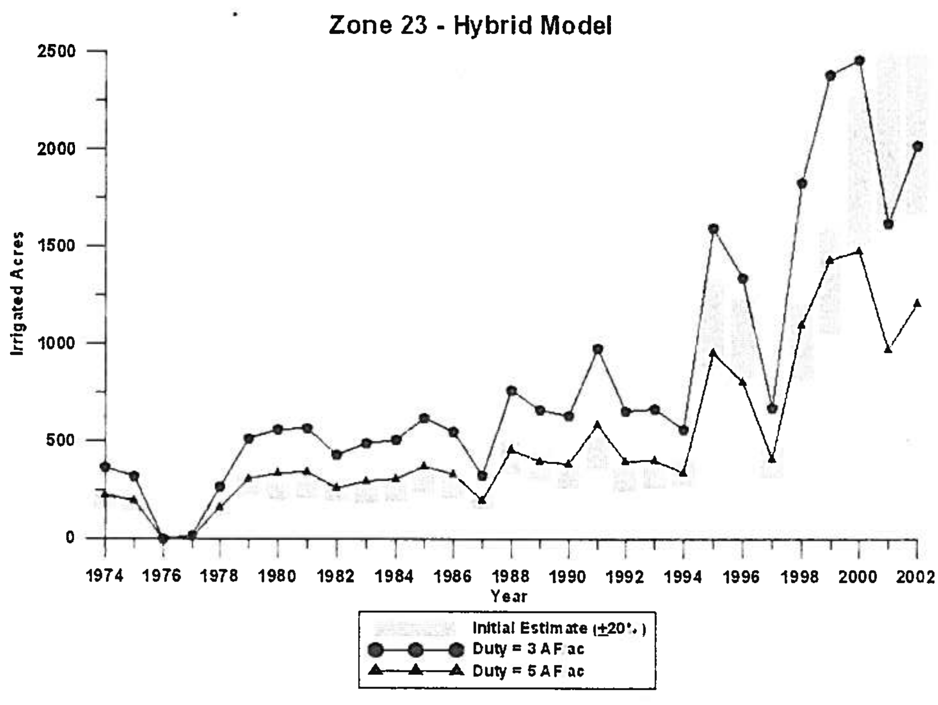

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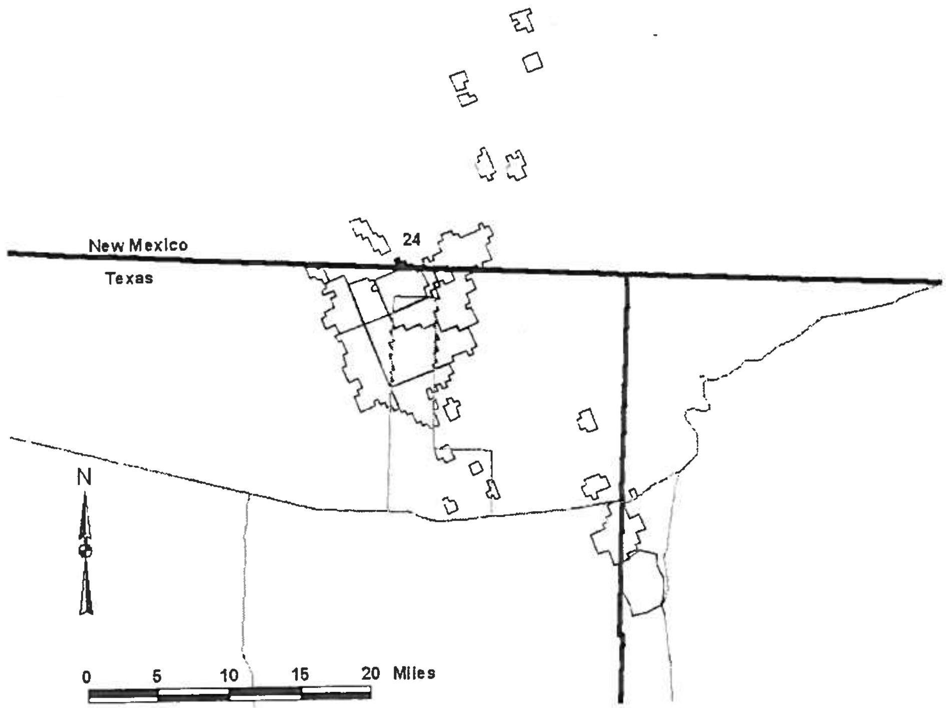

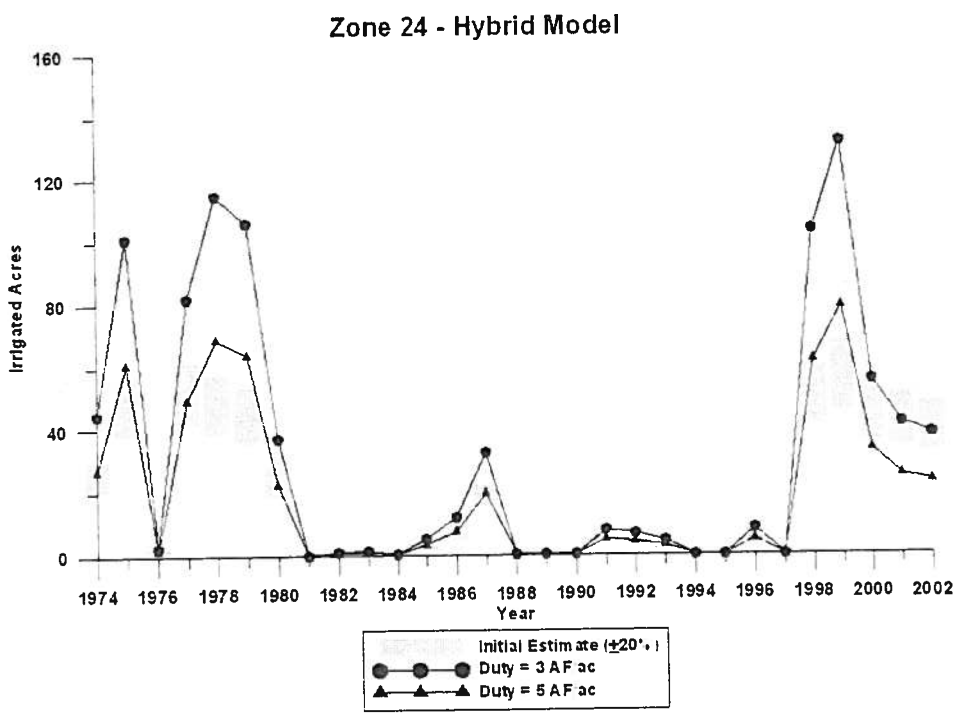

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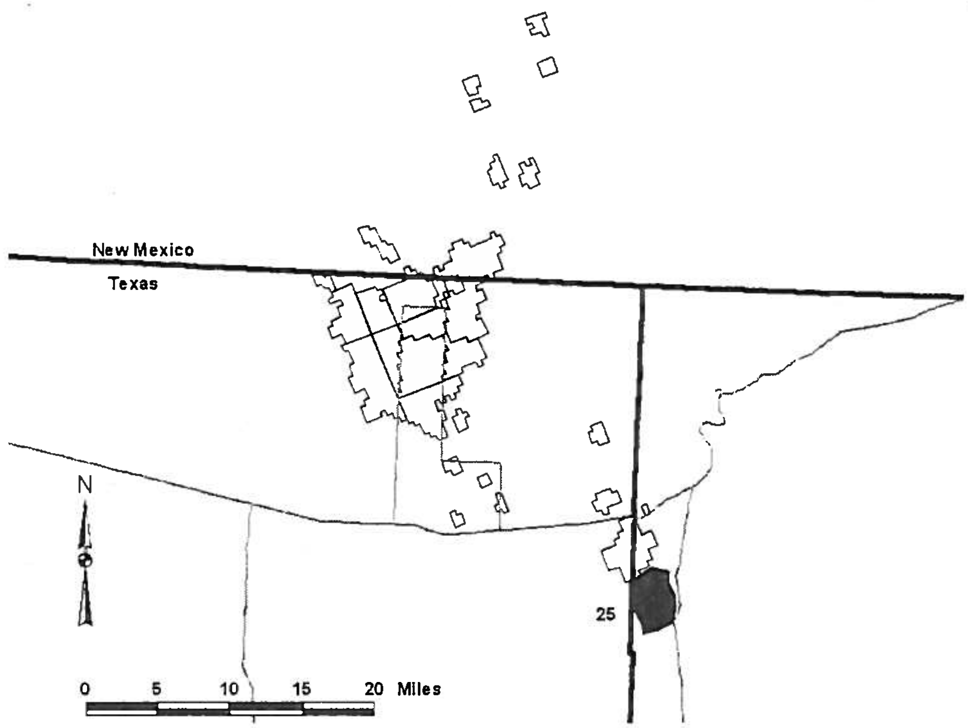
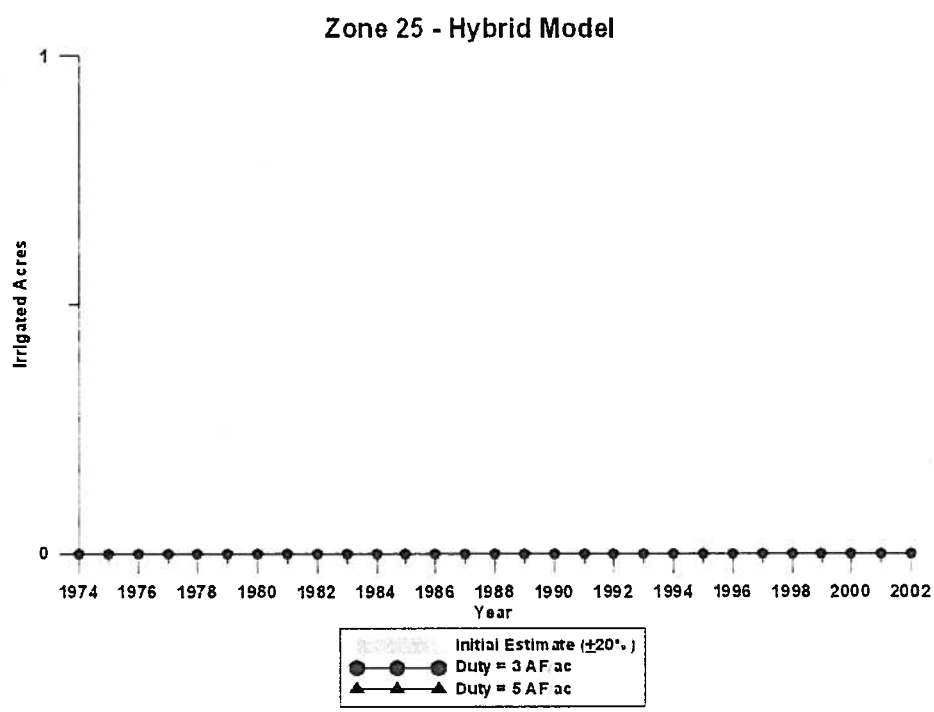




Note: Initial Estimate Range from Groeneveld and Baugh (2002)

Appendix C

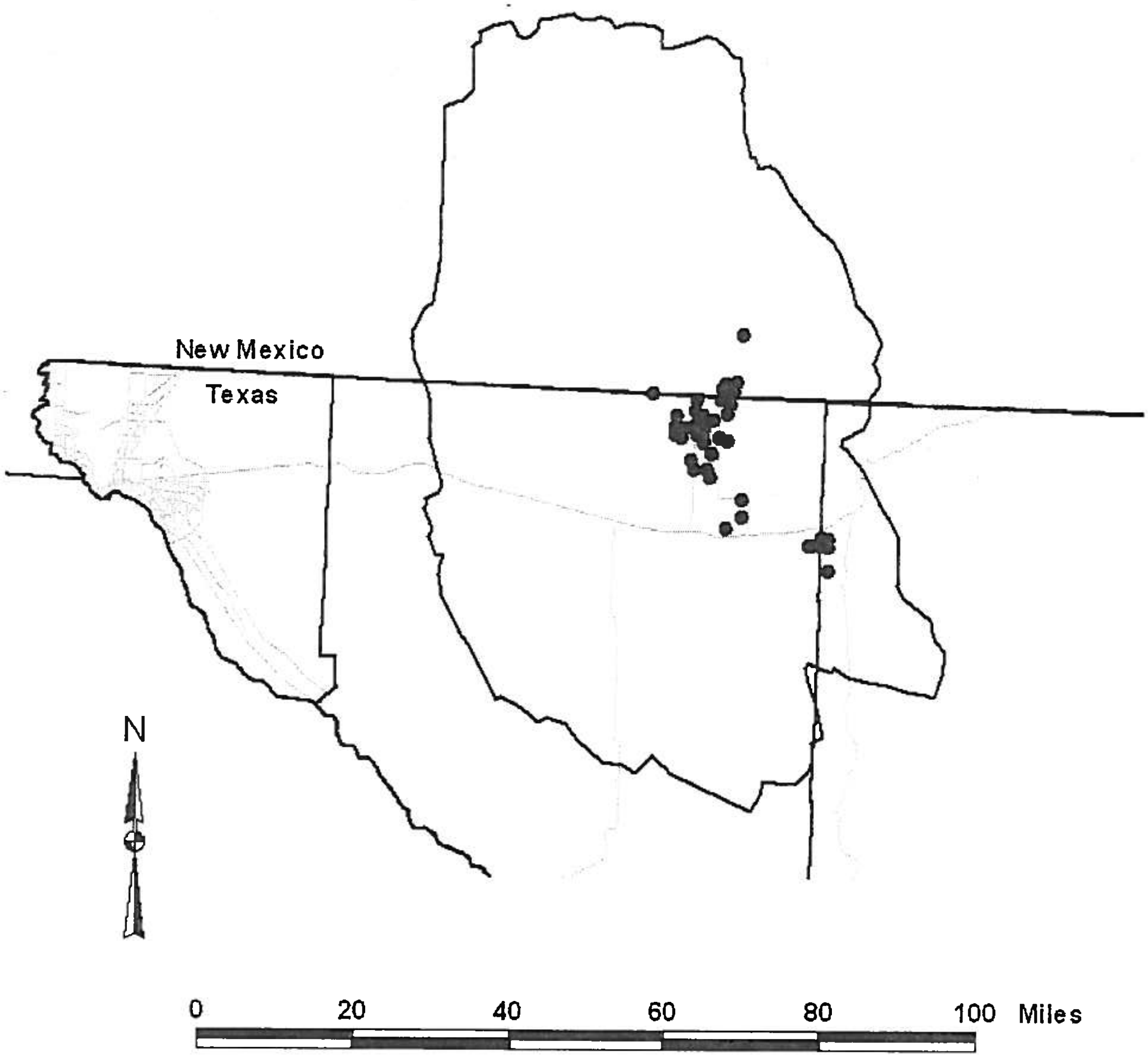
Hydrographs of Measured Groundwater Elevations and Model Estimated Groundwater Elevations with Location Maps and Data

Summary of Wells with Hydrographs of Actual Groundwater Elevation and Model Estimated Groundwater Elevation Hydrographs (New Mexico Wells)

Well Number	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (ft MSL)	Lowest Groundwater Elevation (ft MSL)	Year of Earliest Measurement	Year of Latest Measurement
25S.18E.21.233	131	128	30	3593	3617	1958	1992
26S.18E.21.313	145	120	44	3598	3626	1955	1999
26S.18E.30.122	144	117	22	3532	3557	1955	1994
26S.18E.30.321	145	115	24	3557	3582	1949	1999
26S.18E.32.122	147	118	26	3562	3588	1955	1984

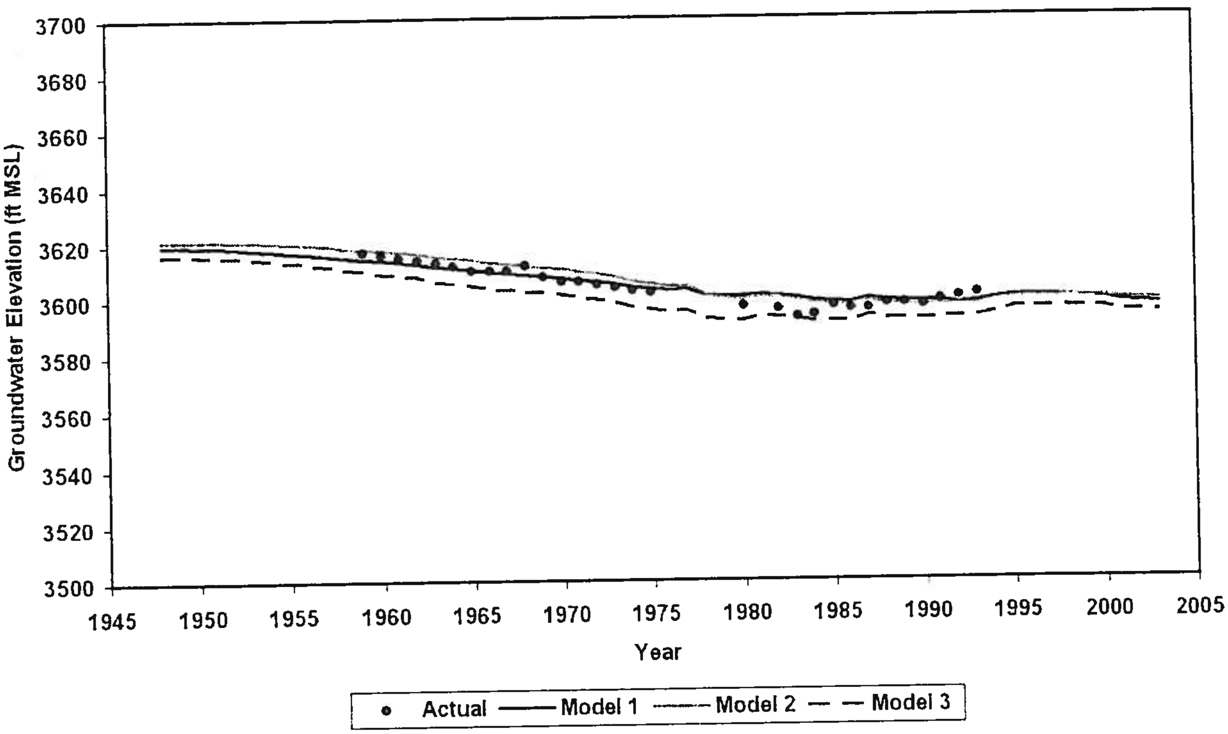
Summary of Wells with Hydrographs of Actual Groundwater Elevation and Model Estimated Groundwater Elevation Hydrographs (Texas Wells)

Well Number	Model Row	Model Column	Number of Measurements	Highest Groundwater Elevation (ft MSL)	Lowest Groundwater Elevation (ft MSL)	Year of Earliest Measurement	Year of Latest Measurement
47-17-202	206	122	45	3564	3612	1953	2002
47-17-203	207	126	33	3583	3614	1957	1995
47-17-205	206	123	43	3579	3625	1953	1999
47-17-206	206	126	41	3585	3613	1959	2002
47-17-302	209	128	38	3569	3607	1957	2002
47-17-304	206	129	32	3591	3608	1964	2000
47-17-317	205	127	27	3571	3607	1964	1995
47-17-601	216	125	30	3591	3627	1958	1994
48-06-201	138	92	23	3603	3660	1953	1988
48-07-102	148	97	25	3577	3602	1963	2002
48-07-203	145	106	50	3580	3625	1947	1995
48-07-206	146	105	43	3566	3634	1947	2002
48-07-207	149	104	41	3578	3605	1959	2002
48-07-214	151	106	26	3579	3603	1966	1993
48-07-301	148	113	45	3581	3625	1947	1995
48-07-304	154	113	42	3574	3614	1953	2002
48-07-402	155	96	29	3588	3619	1947	1973
48-07-403	151	100	25	3584	3624	1947	1974
48-07-405	153	98	47	3577	3624	1947	2002
48-07-414	154	94	25	3581	3604	1963	1994
48-07-418	151	95	33	3579	3603	1966	2002
48-07-501	156	101	51	3578	3626	1947	2002
48-07-502	156	104	55	3574	3621	1947	2002
48-07-504	154	101	36	3582	3626	1947	1984
48-07-505	156	101	26	3579	3616	1953	1992
48-07-516	153	102	37	3566	3601	1966	2002
48-07-606	154	108	55	3576	3627	1947	2002
48-07-607	160	108	40	3578	3606	1959	2002
48-07-708	164	96	29	3562	3599	1966	2002
48-07-801	159	102	37	3571	3621	1947	2002
48-07-803	162	98	47	3585	3625	1952	2002
48-07-901	162	110	40	3577	3602	1958	2002
48-07-904	164	103	42	3584	3617	1949	2002
48-08-102	151	116	31	3582	3601	1966	1998
48-15-201	169	100	37	3582	3607	1959	1999
48-15-203	167	96	36	3568	3617	1953	1995
48-15-301	171	100	41	3586	3612	1959	2002
48-15-302	172	105	25	3581	3604	1963	1993
48-15-902	190	98	32	3549	3590	1959	2002
48-16-402	183	107	25	3593	3617	1959	1993
48-16-702	188	105	25	3586	3608	1959	1994

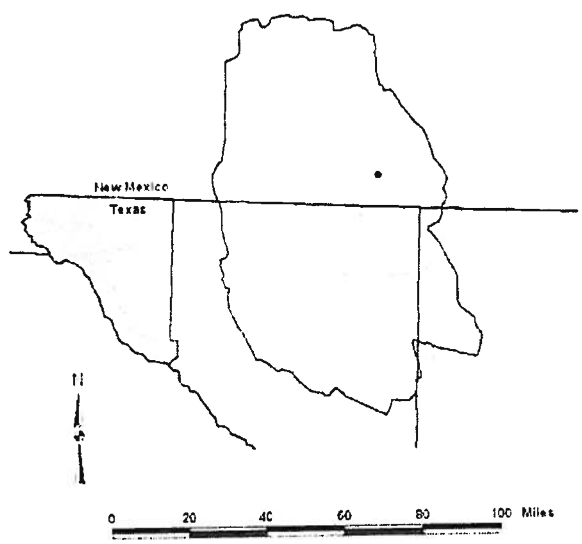


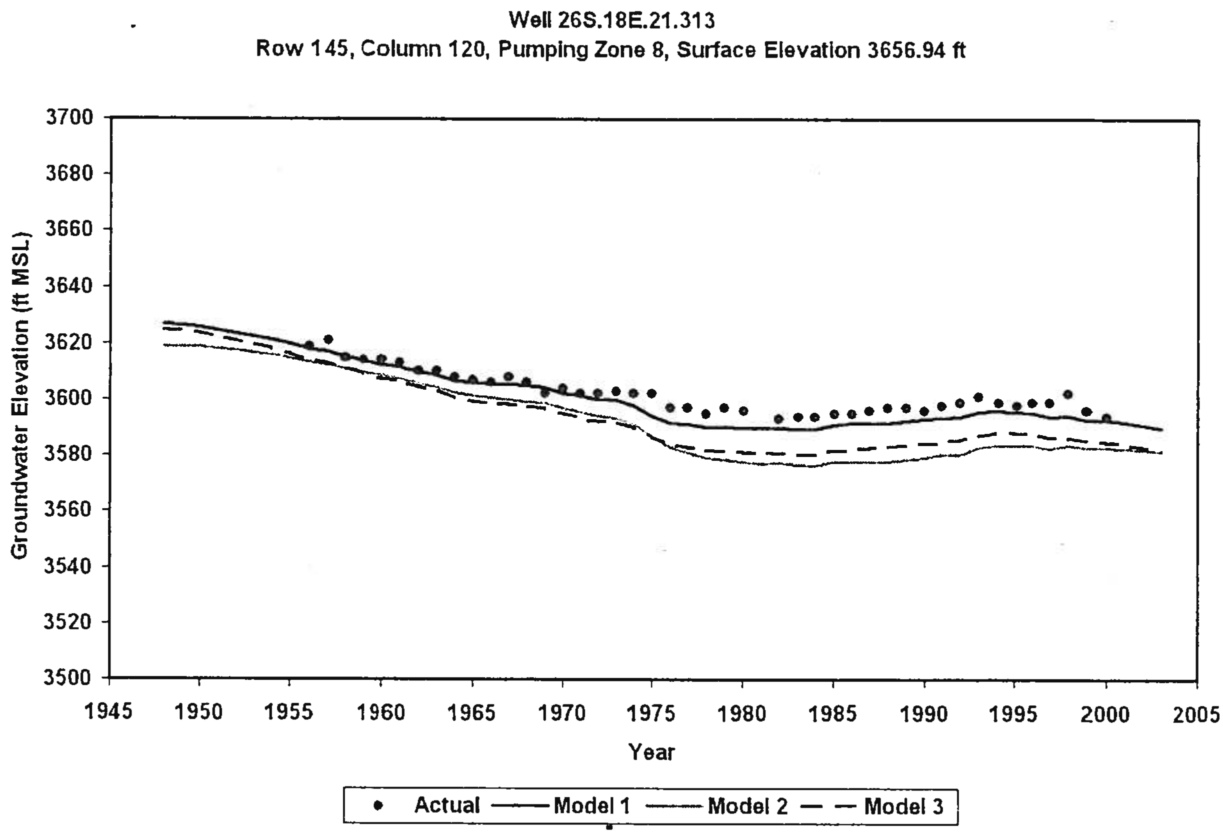
Location of Wells used in Hydrograph Analysis Presented in this Appendix

Well 25S.18E.21.233
Row 131, Column 128, Pumping Zone N/A, Surface Elevation 3704.37 ft

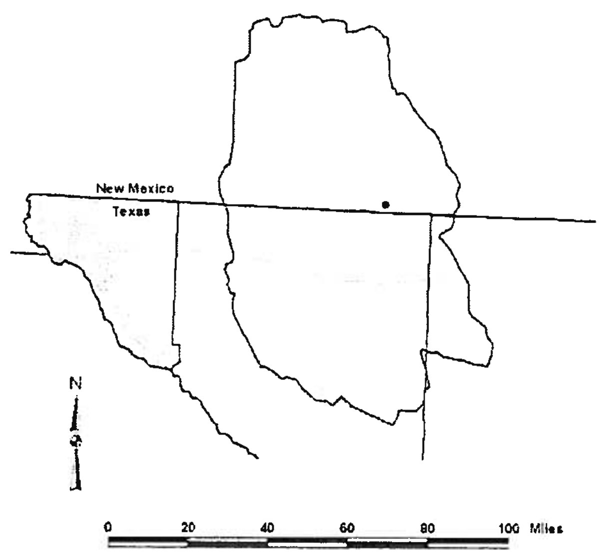


Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

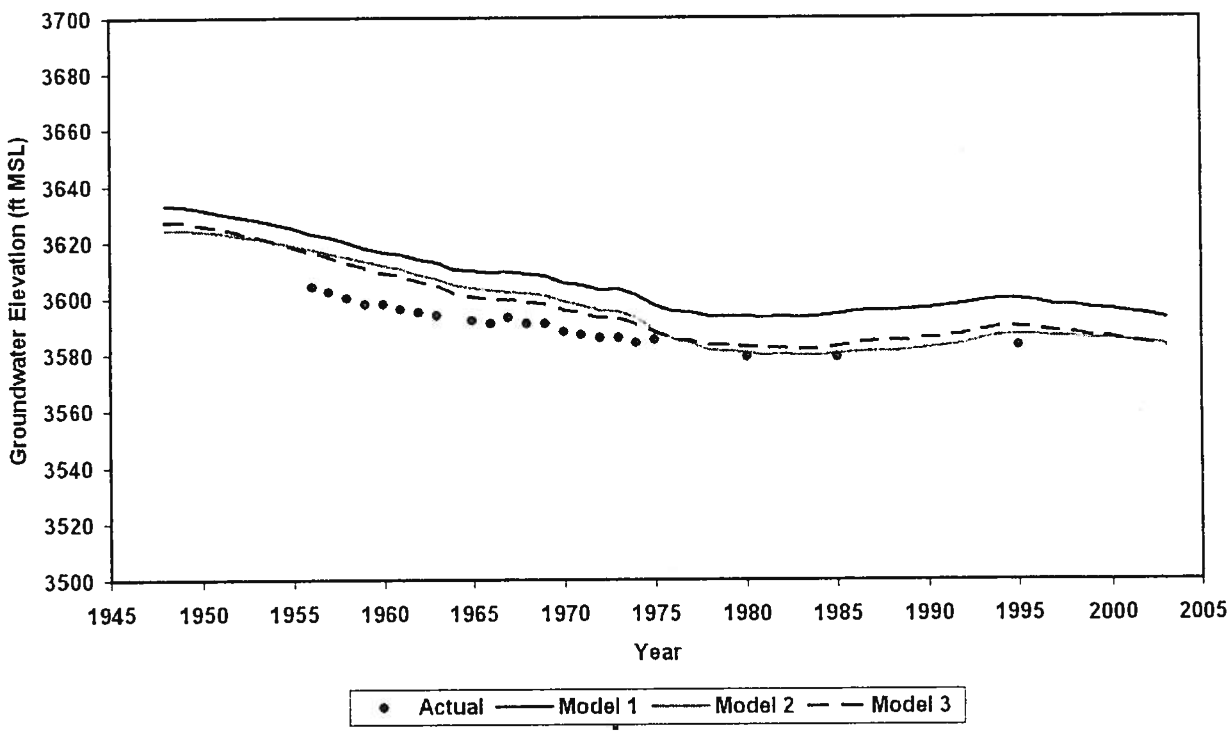




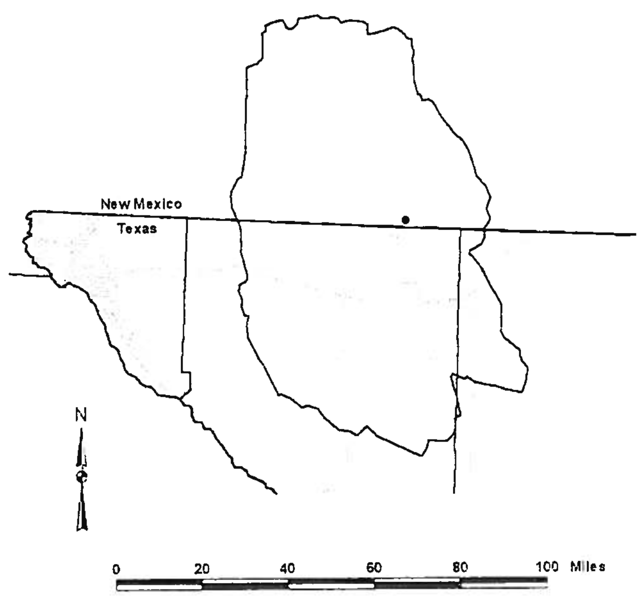
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



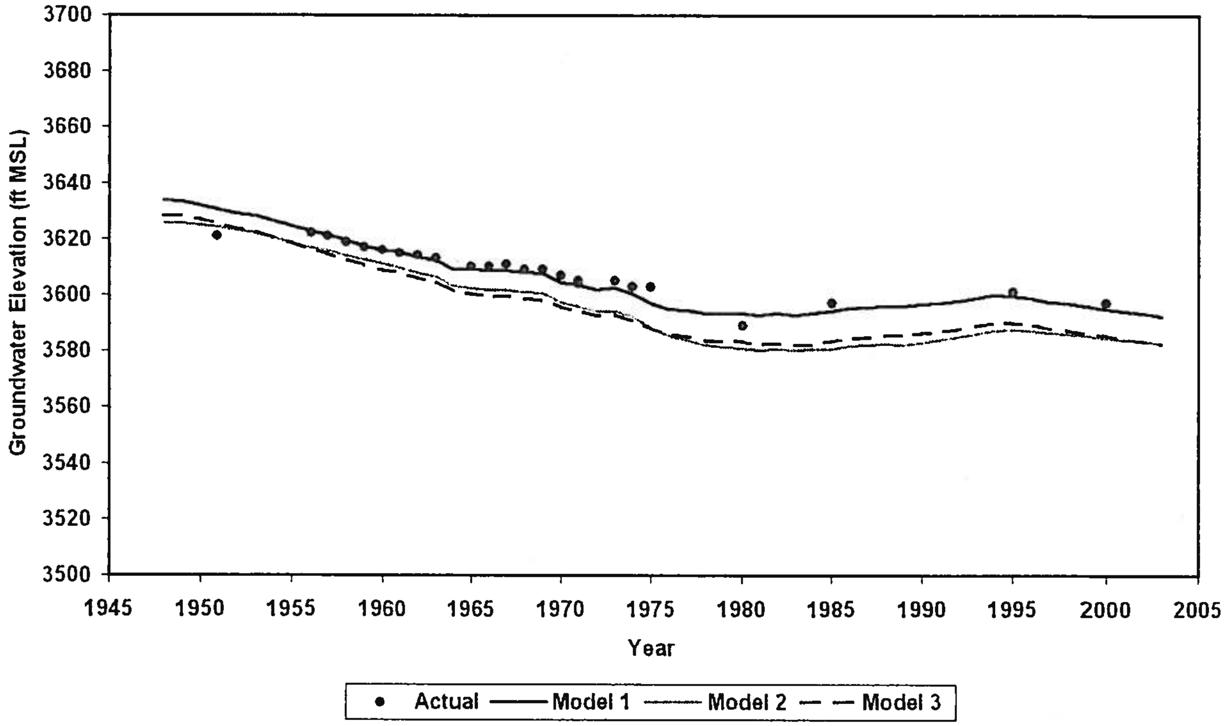
Well 26S.18E.30.122
Row 144, Column 117, Pumping Zone 8, Surface Elevation 3692.73 ft



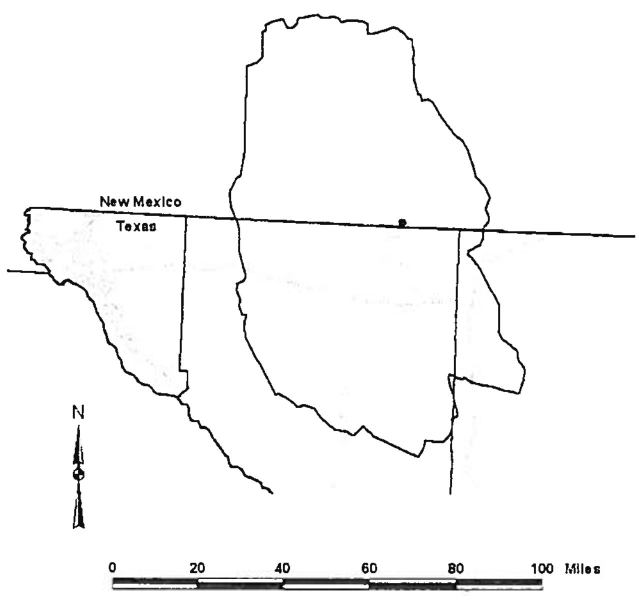
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

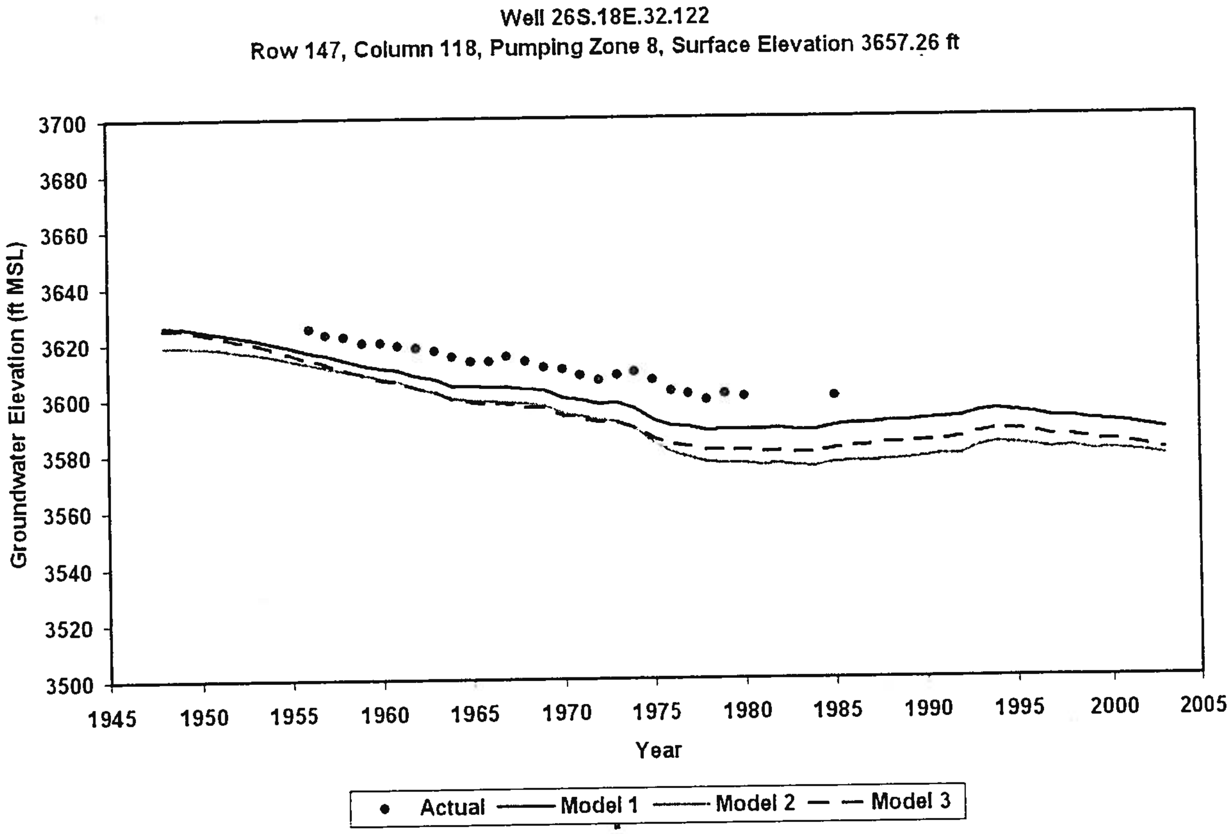


Well 26S.18E.30.321
Row 145, Column 115, Pumping Zone 8, Surface Elevation 3710.82 ft

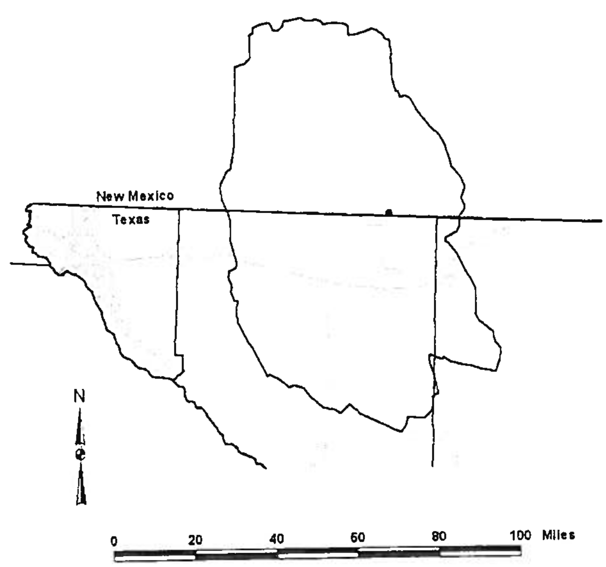


Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

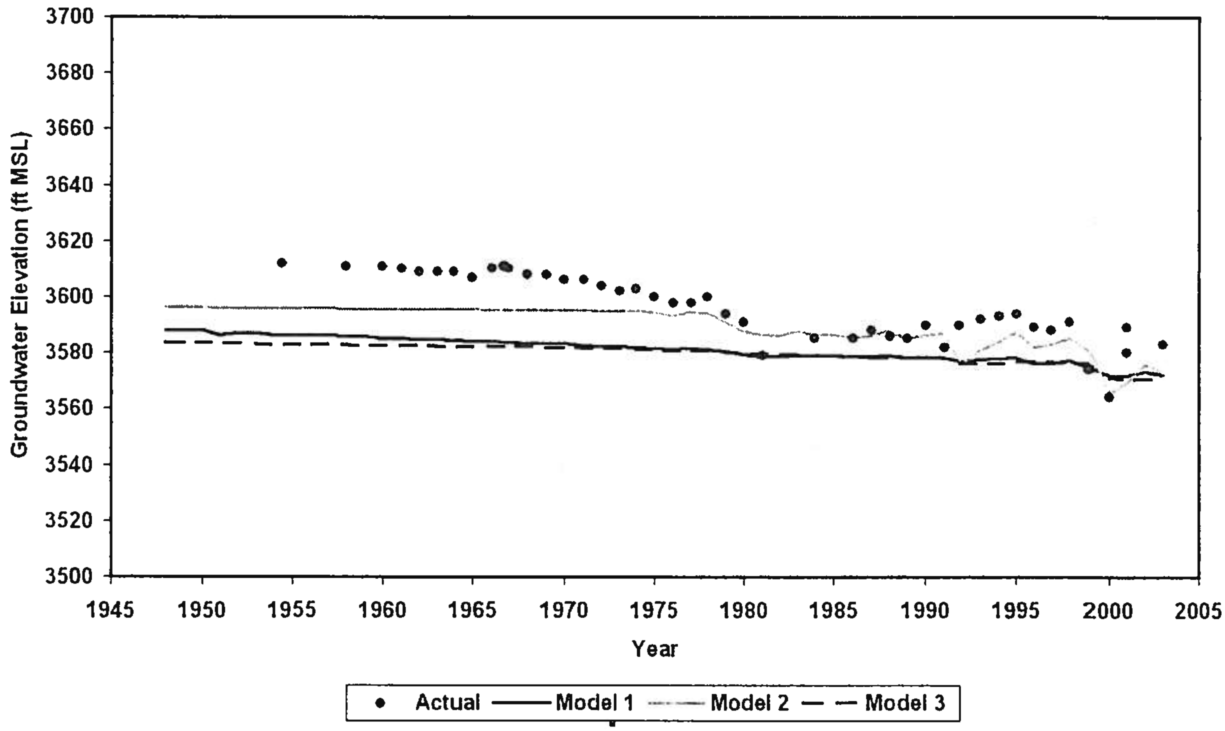




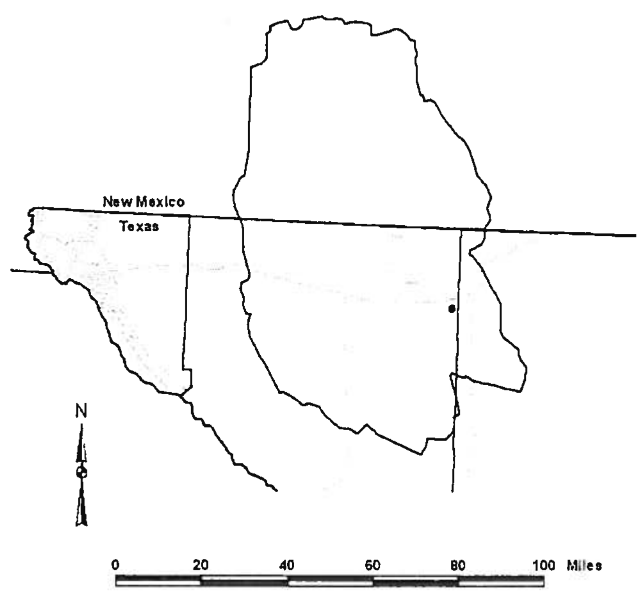
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



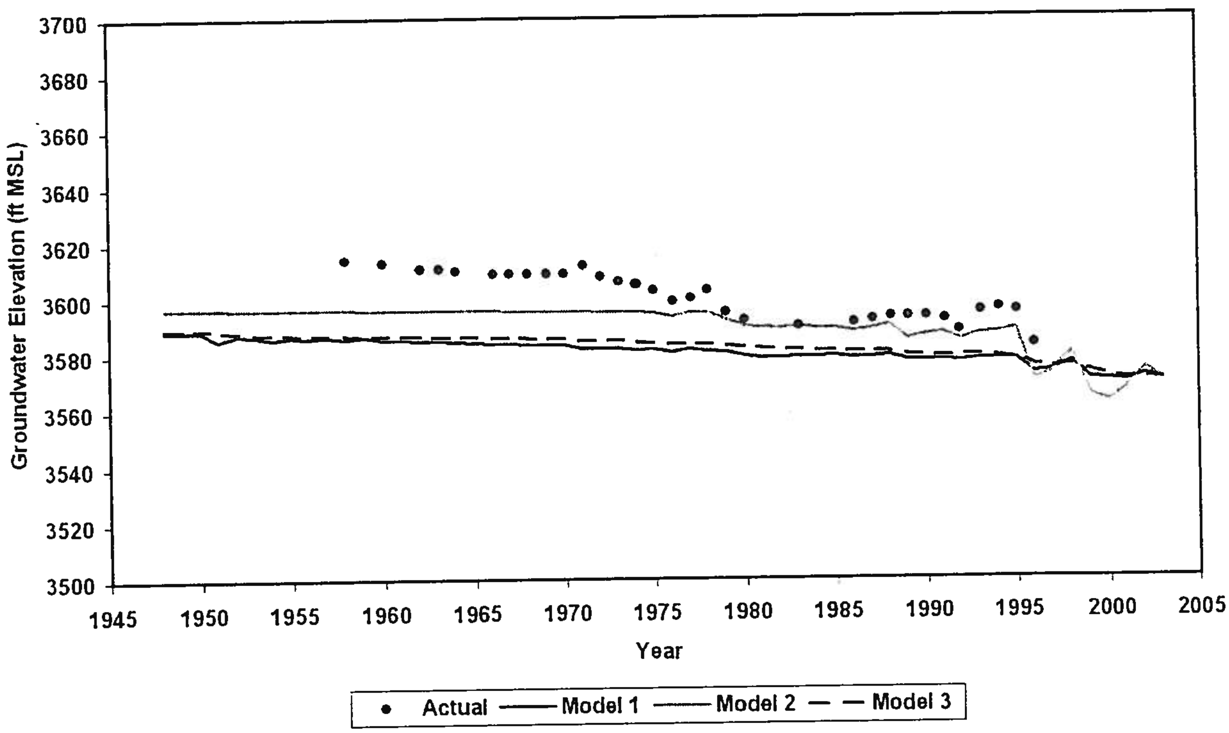
Well 47-17-202
Row 206, Column 122, Pumping Zone 23, Surface Elevation 3659.86 ft



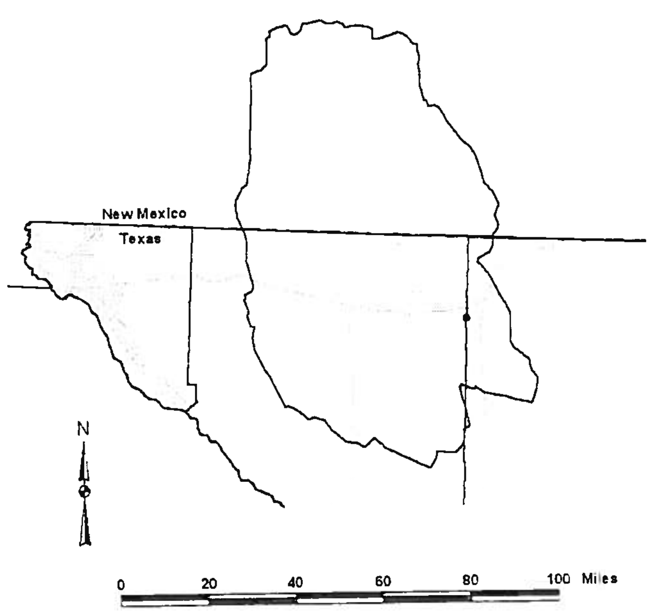
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



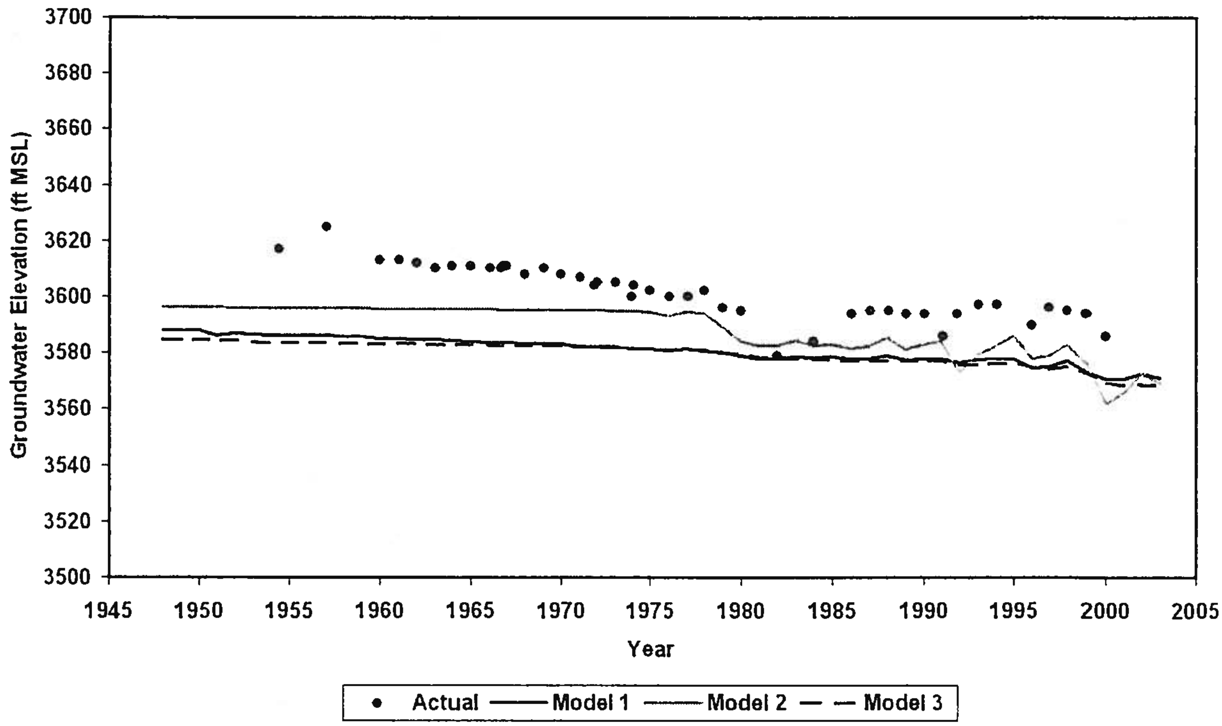
Well 47-17-203
Row 207, Column 126, Pumping Zone 23, Surface Elevation 3750.31 ft



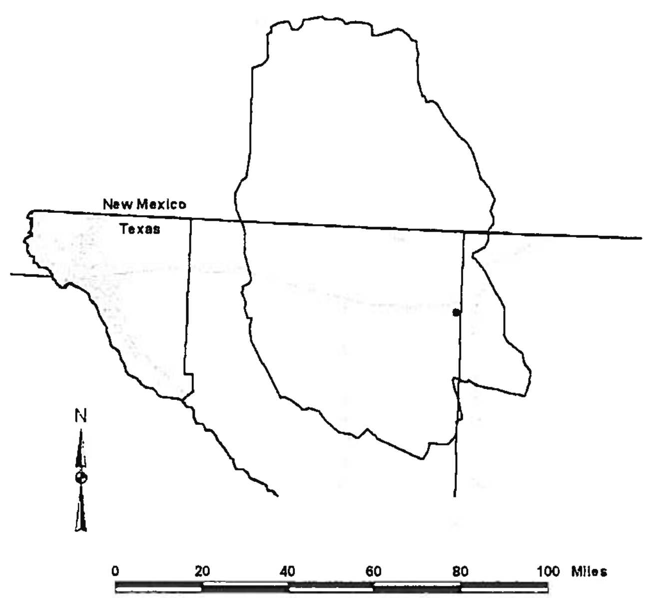
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

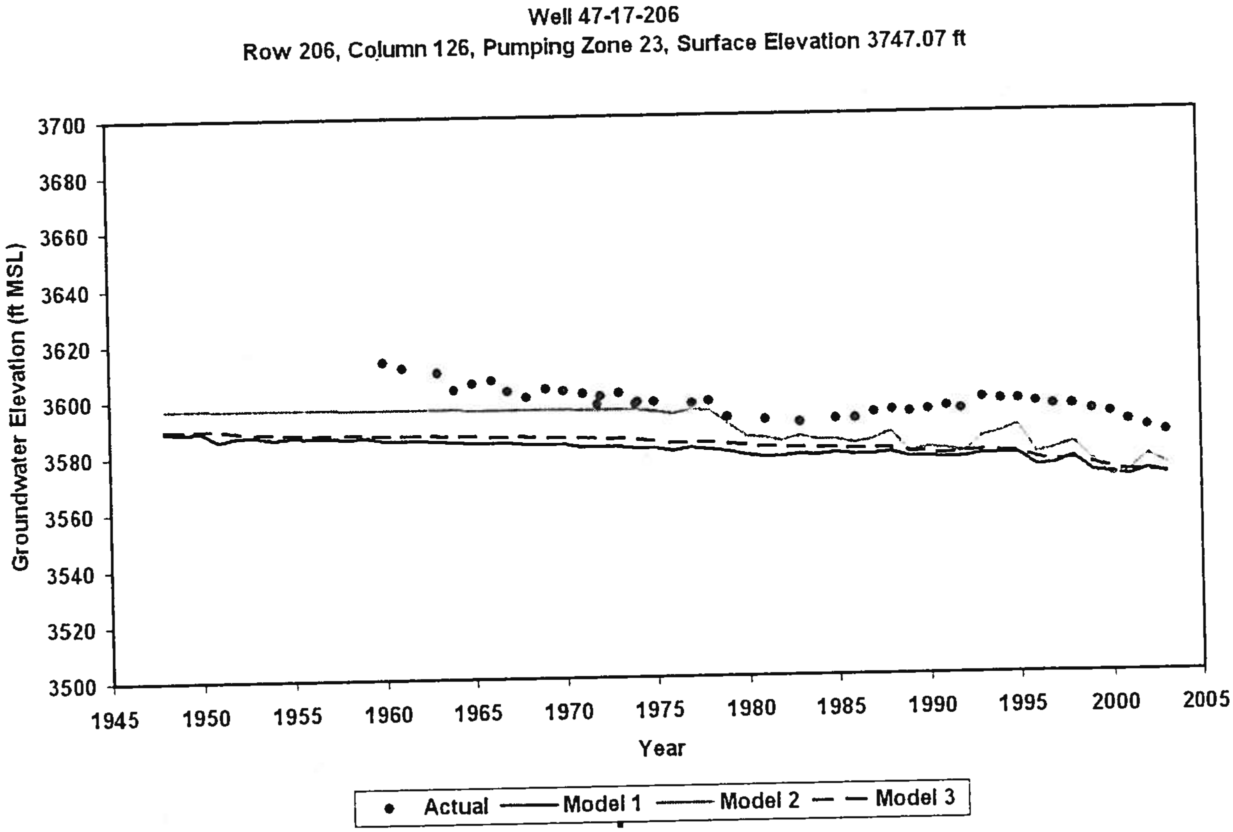


Well 47-17-205
Row 206, Column 123, Pumping Zone 23, Surface Elevation 3681.63 ft

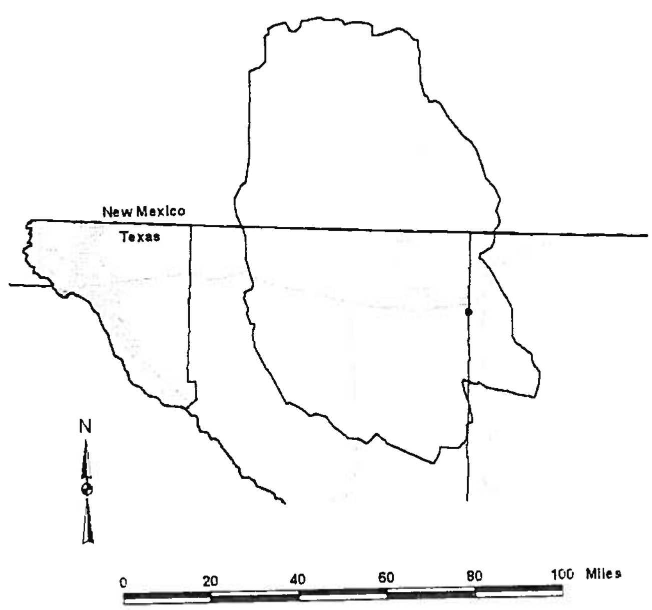


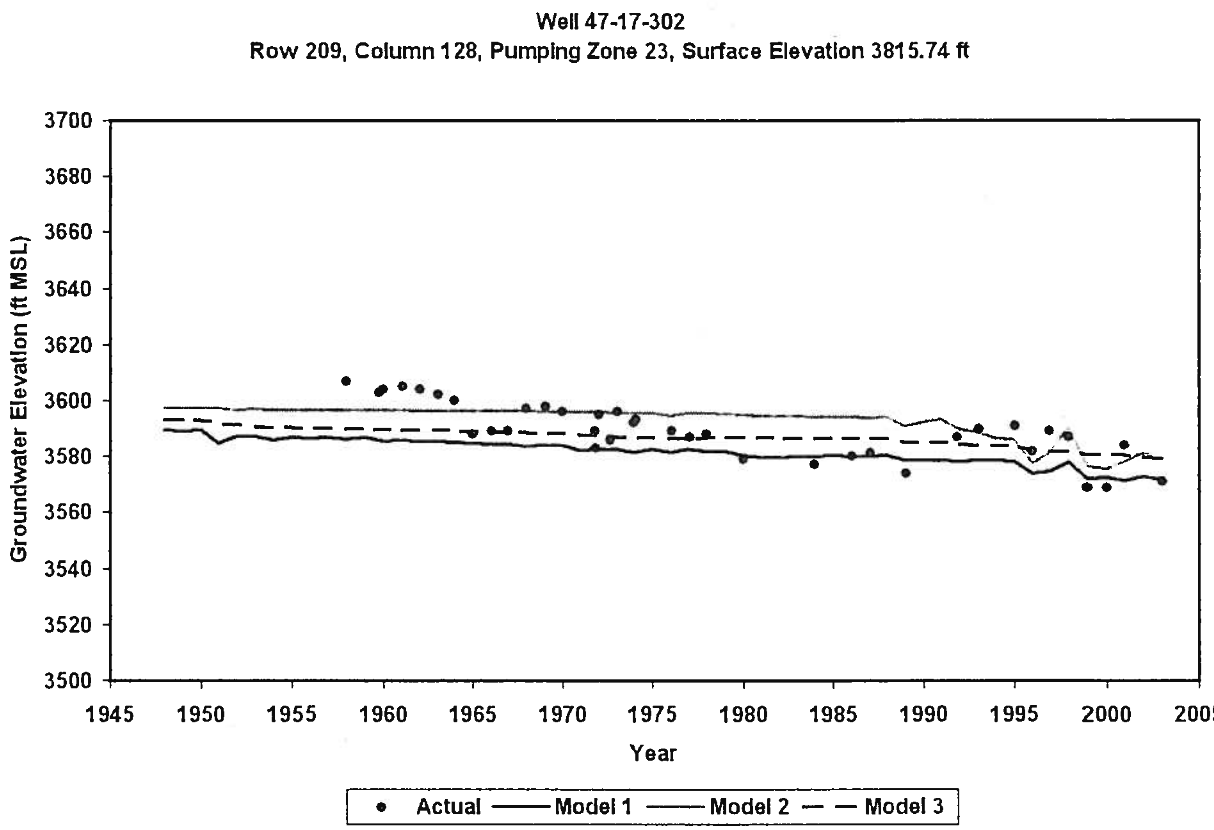
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



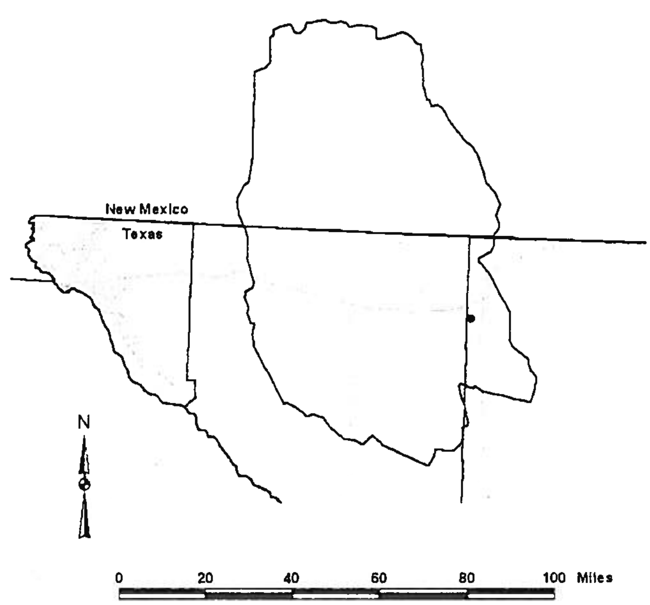


Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

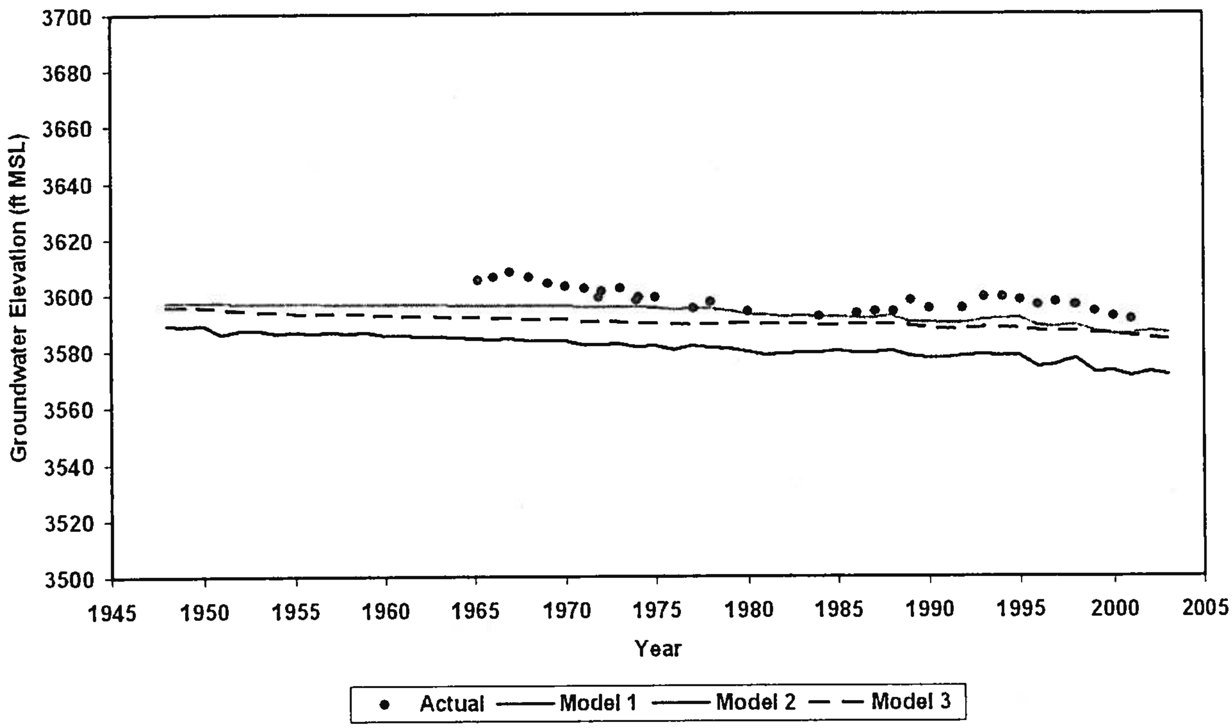




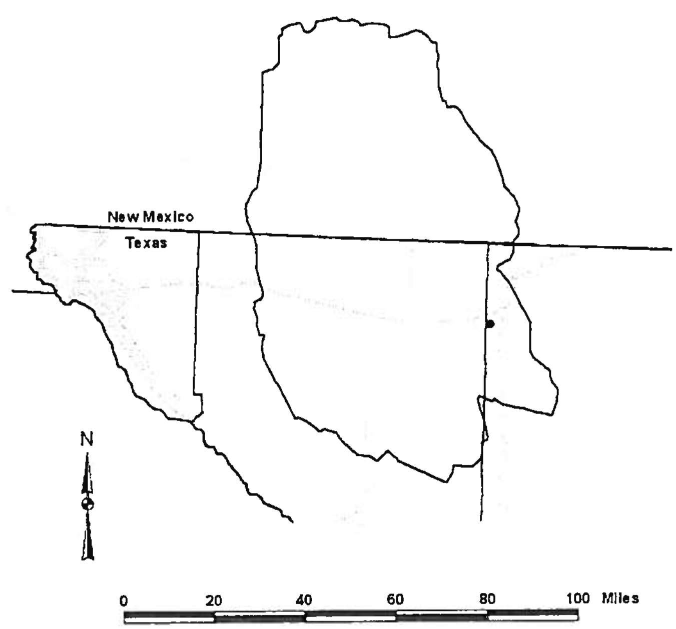
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



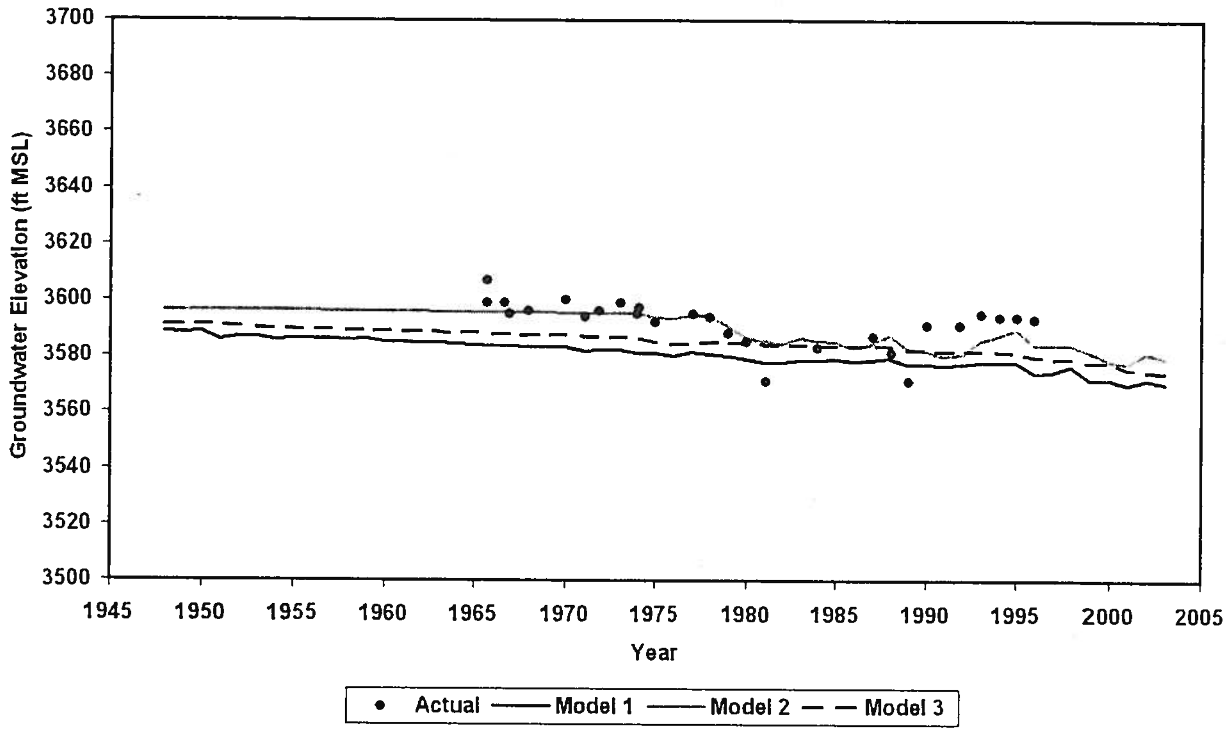
Well 47-17-304
Row 206, Column 129, Pumping Zone 23, Surface Elevation 3841.37 ft



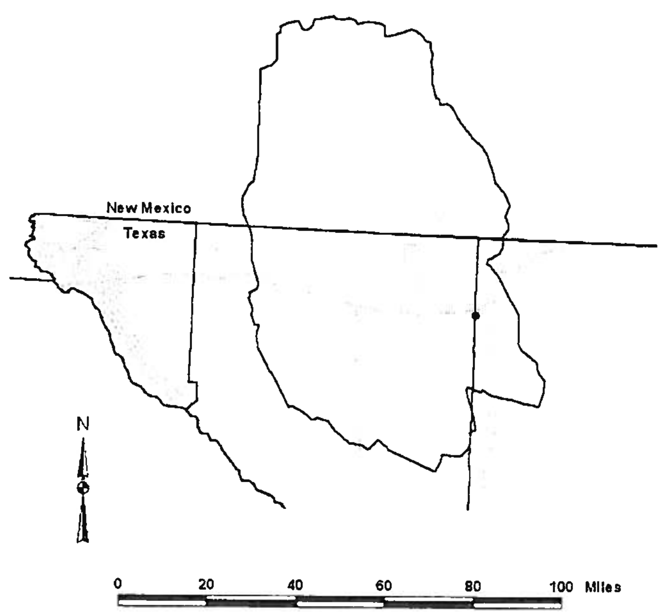
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



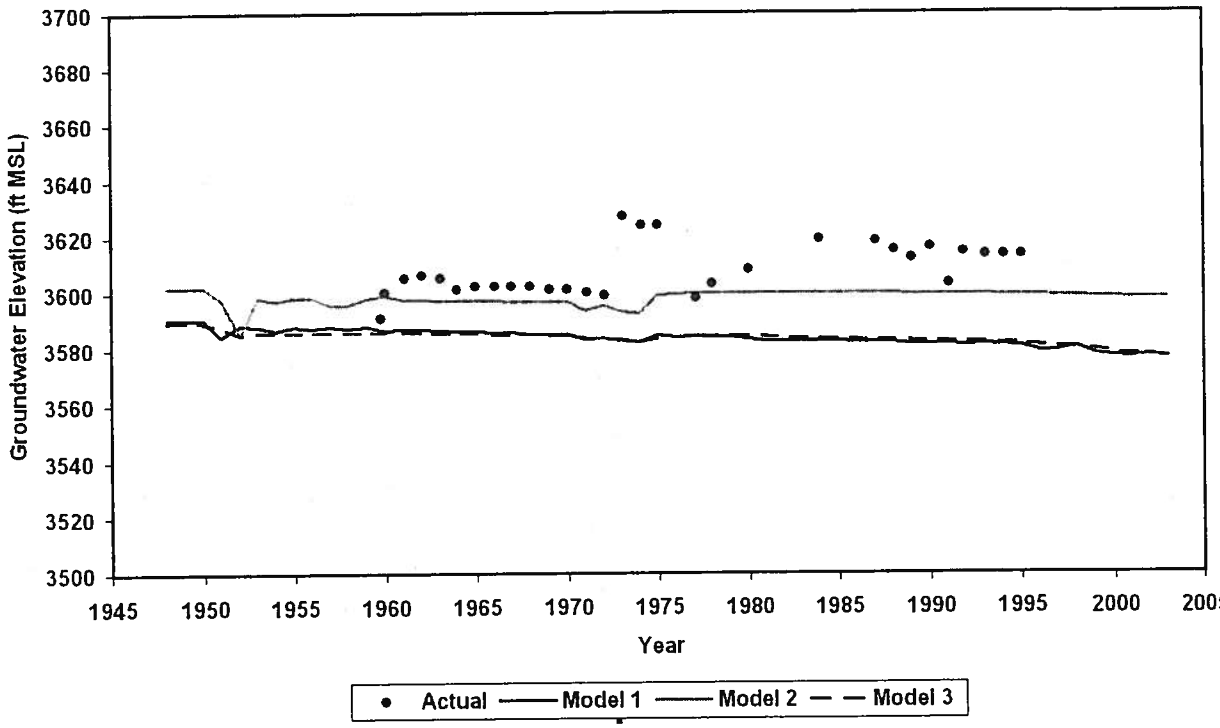
Well 47-17-317
Row 205, Column 127, Pumping Zone 23, Surface Elevation 3765.78 ft



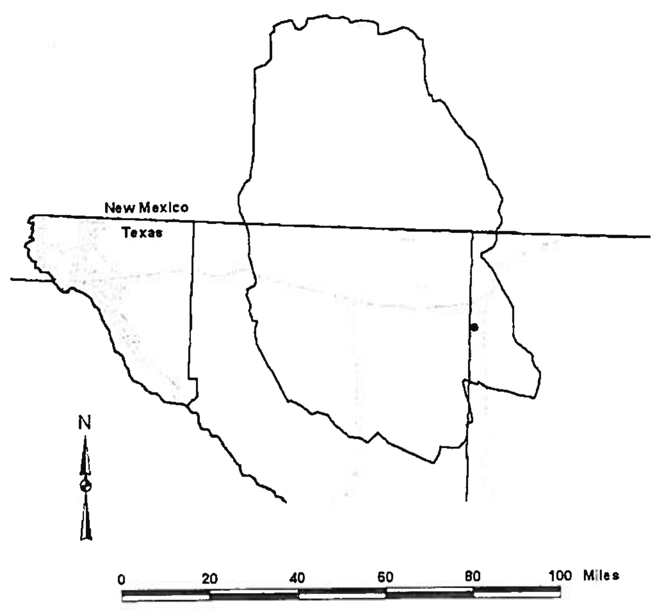
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

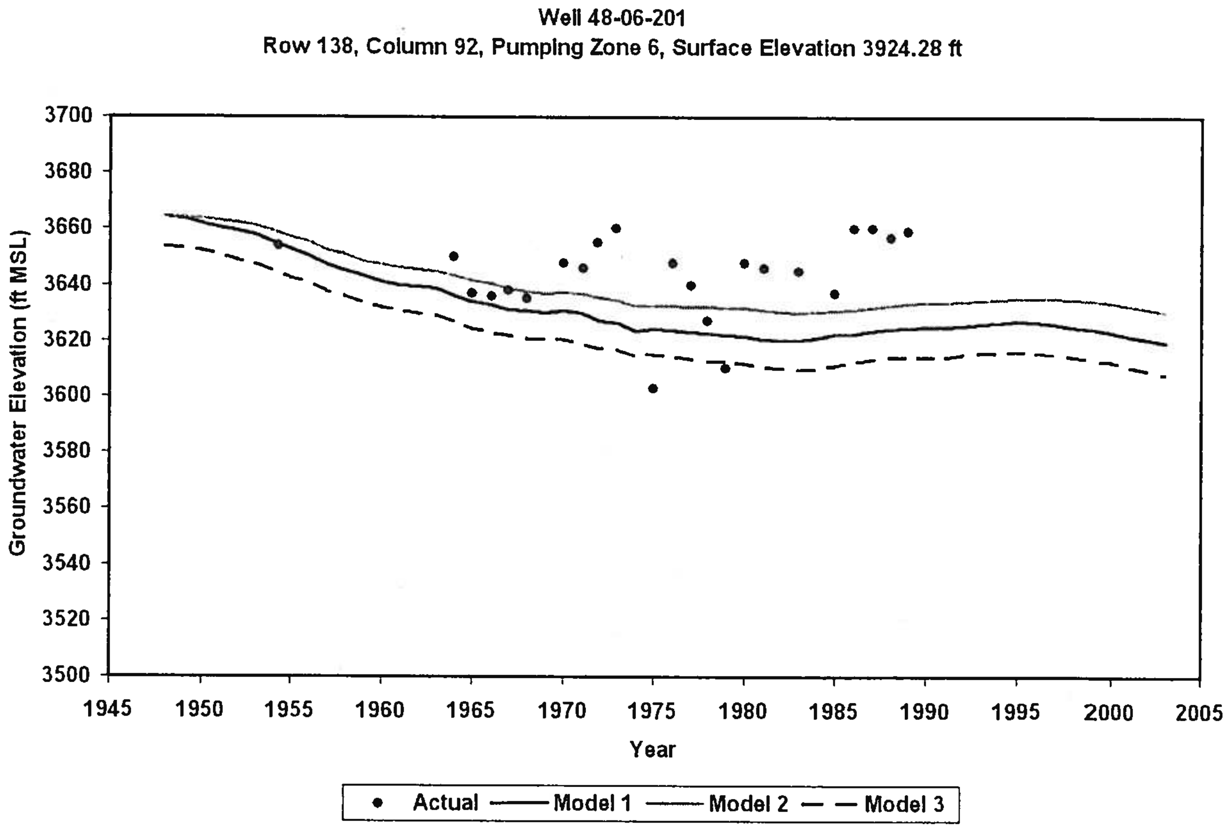


Well 47-17-601
Row 216, Column 125, Pumping Zone N/A, Surface Elevation 3774.08 ft

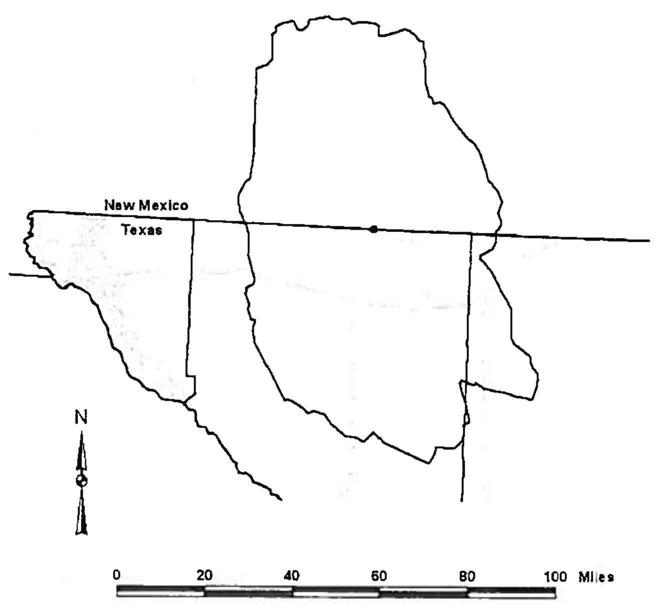


Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

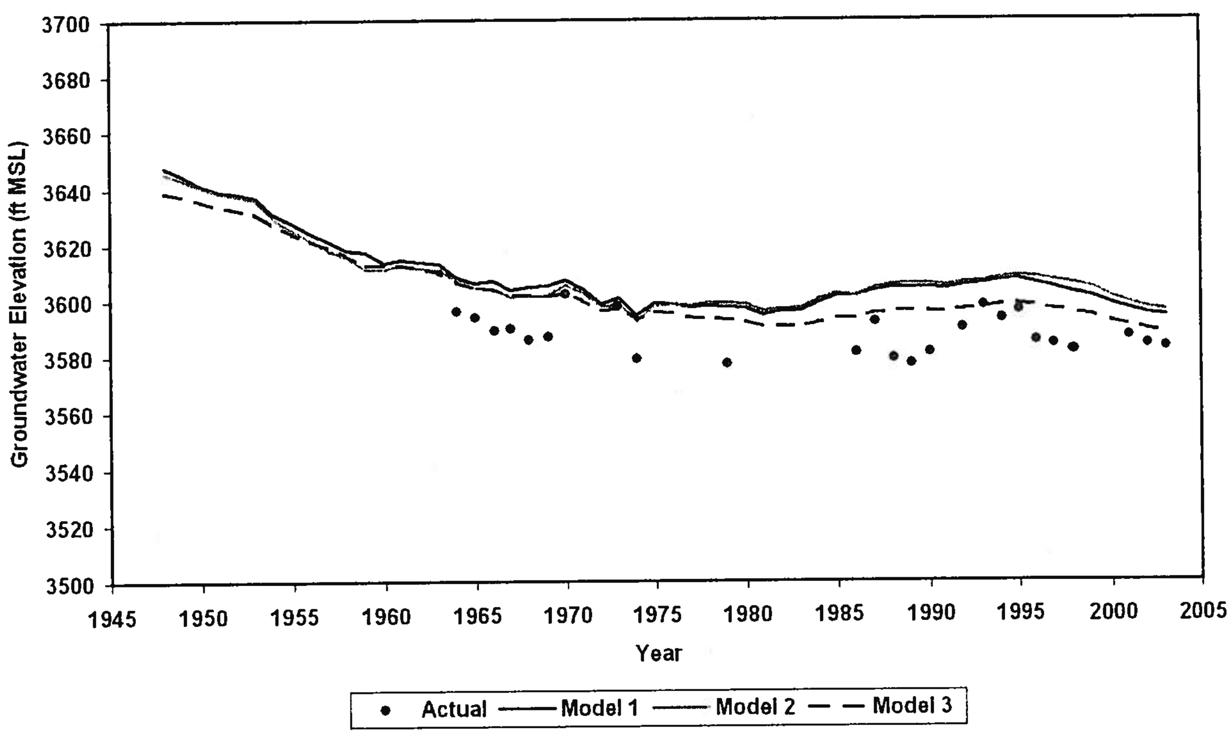




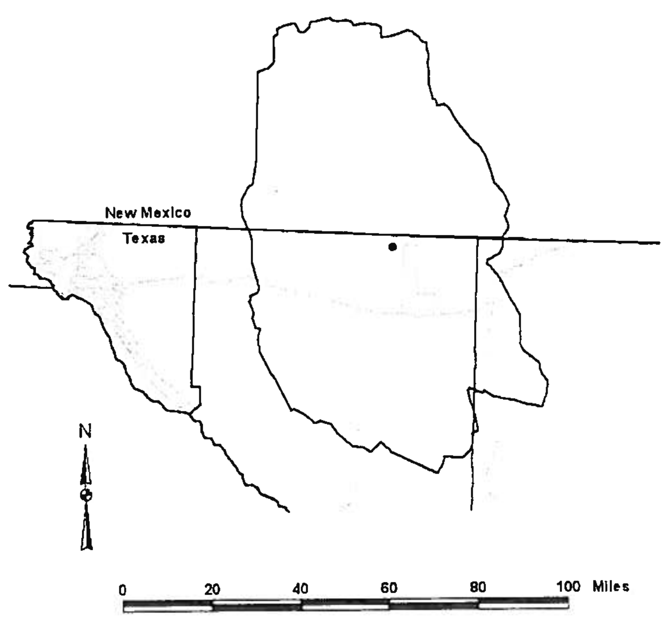
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



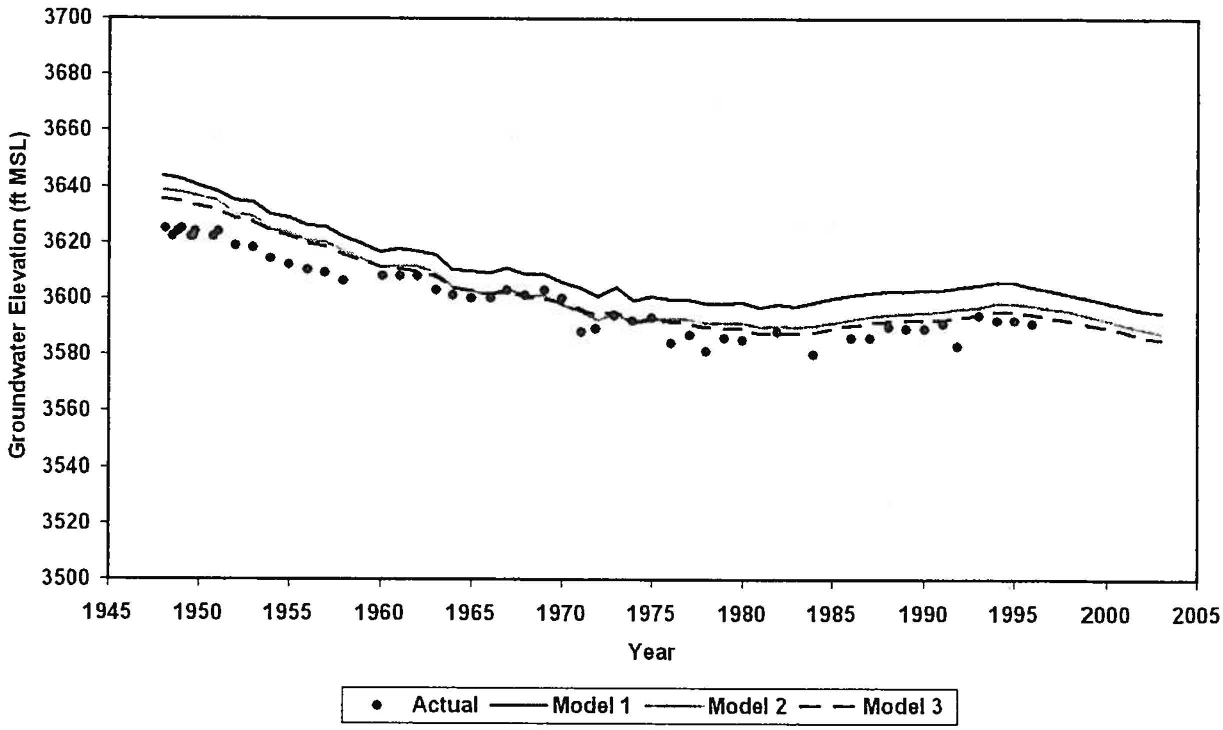
Well 48-07-102
Row 148, Column 97, Pumping Zone 9, Surface Elevation 3769.64 ft



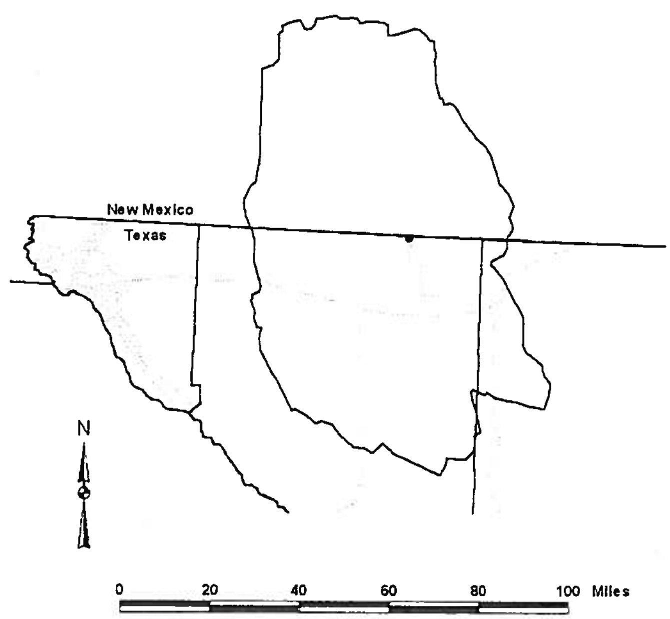
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



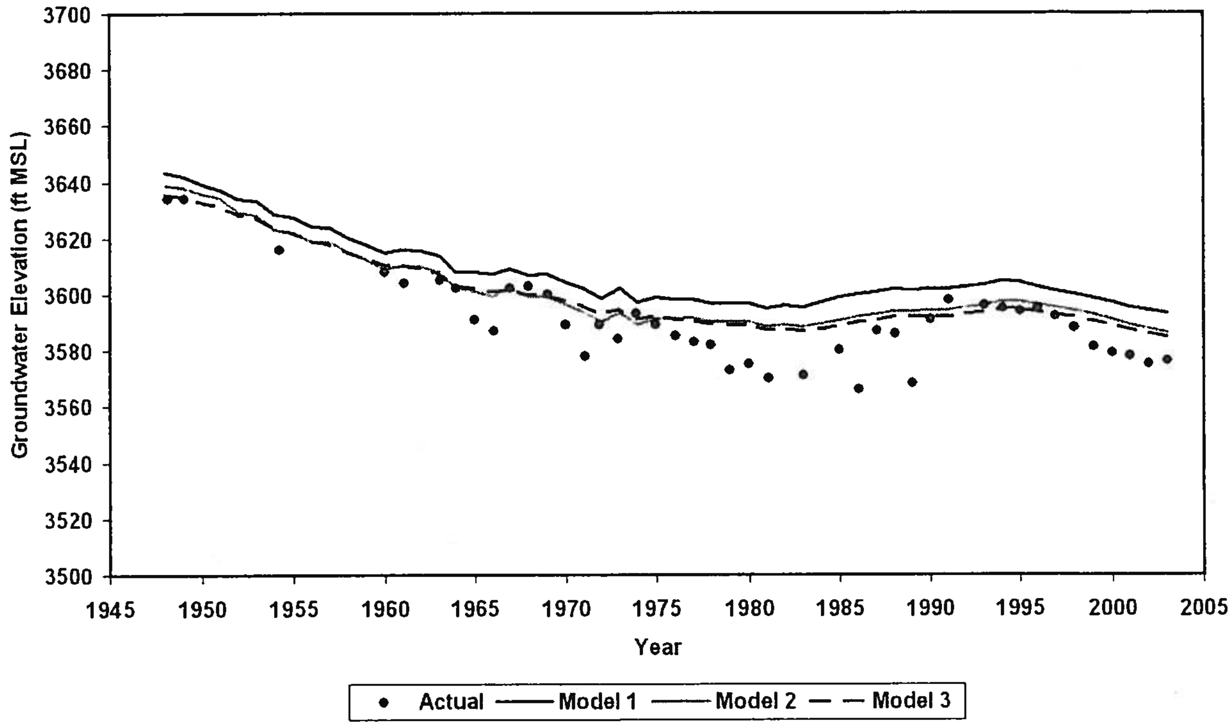
Well 48-07-203
Row 145, Column 106, Pumping Zone 10, Surface Elevation 3747.50 ft



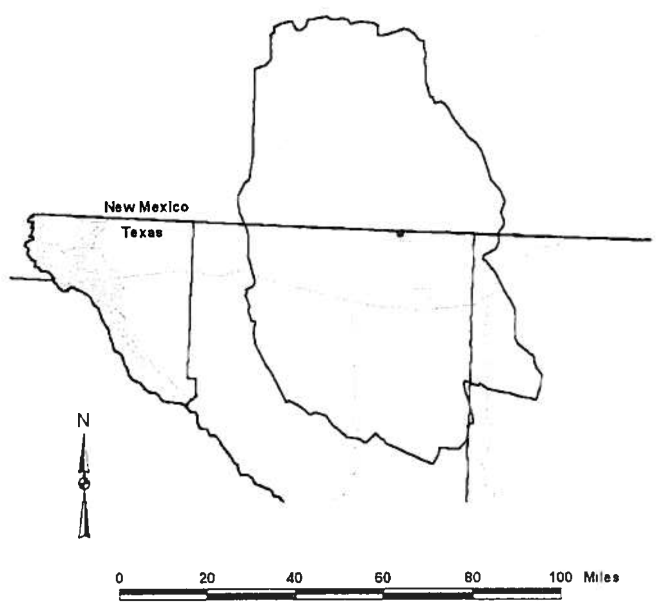
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



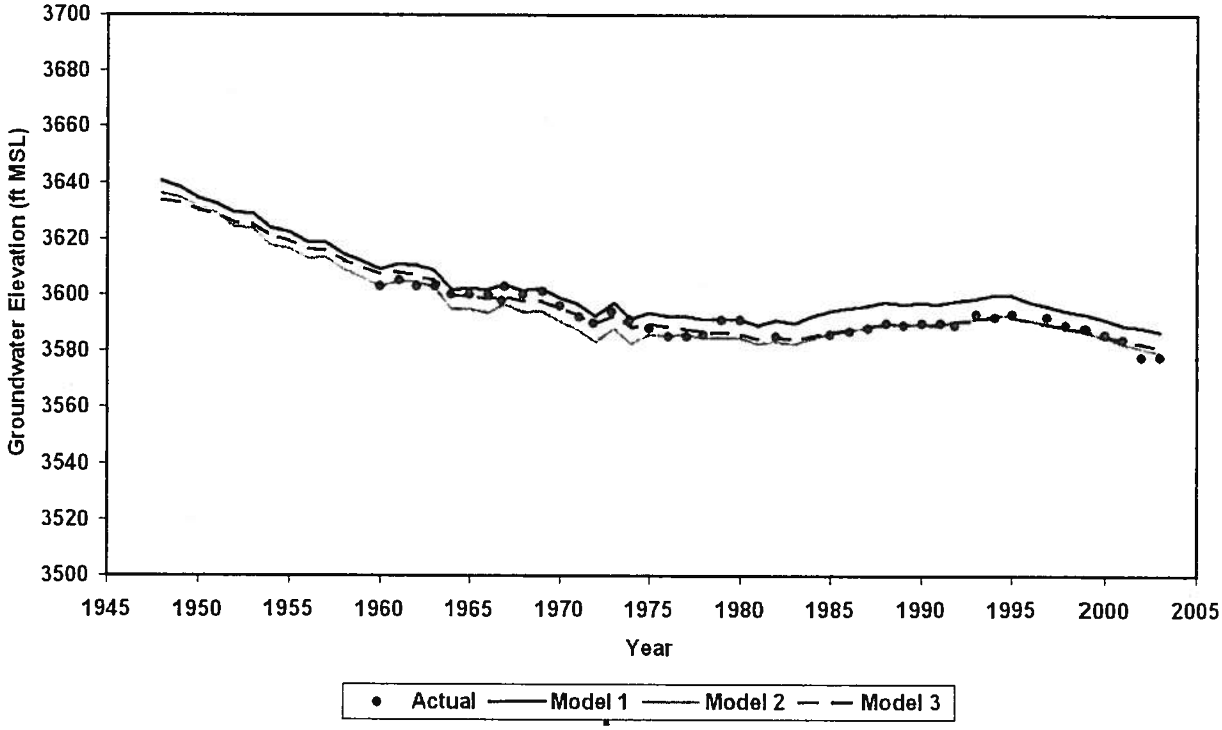
Well 48-07-206
Row 146, Column 105, Pumping Zone 10, Surface Elevation 3724.81 ft



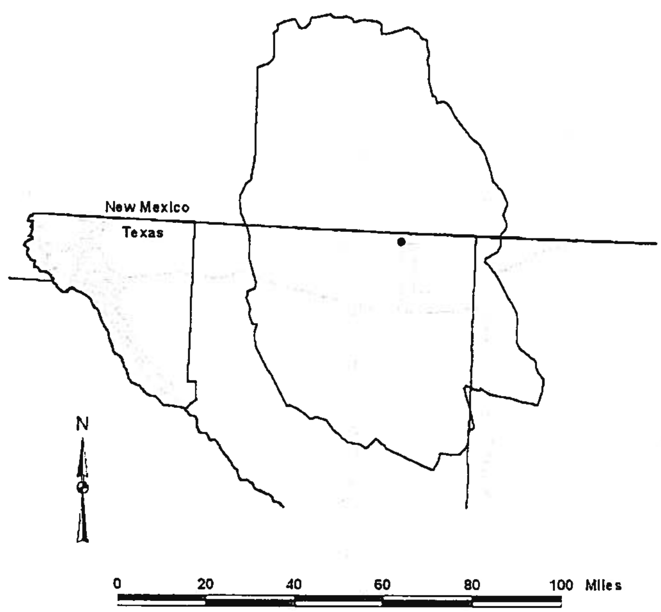
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



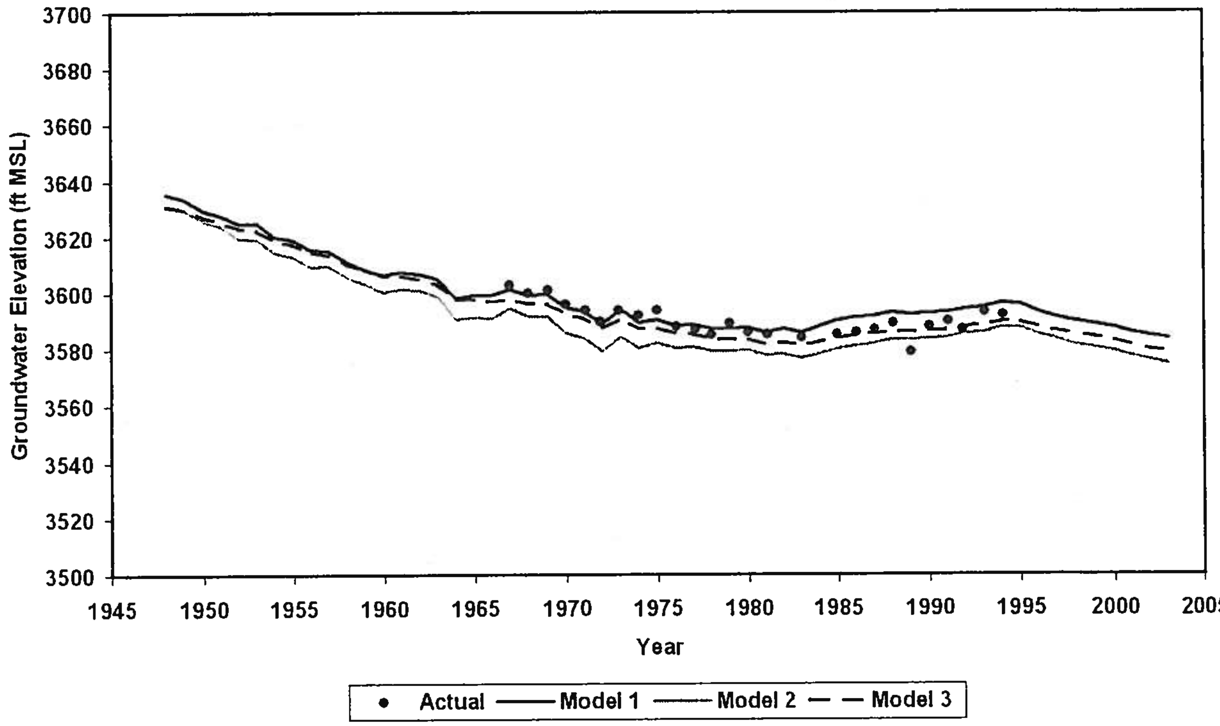
Well 48-07-207
Row 149, Column 104, Pumping Zone 10, Surface Elevation 3688.86 ft



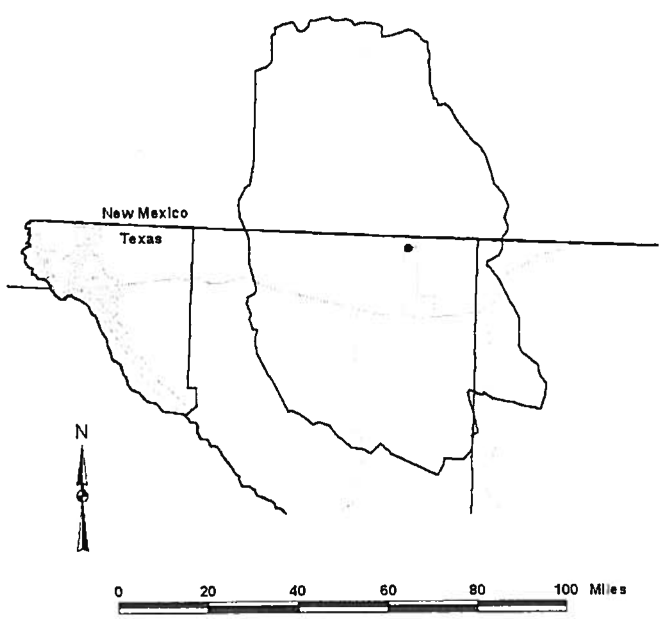
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



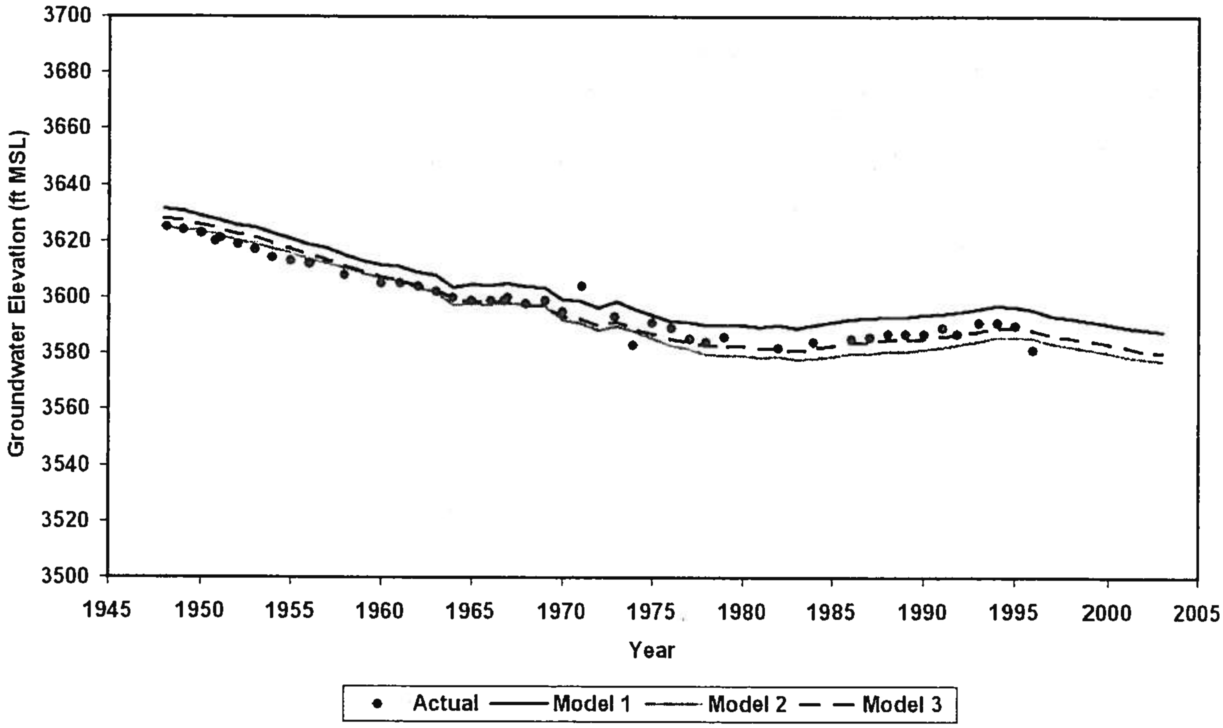
Well 48-07-214
Row 151, Column 106, Pumping Zone 10, Surface Elevation 3654.21 ft



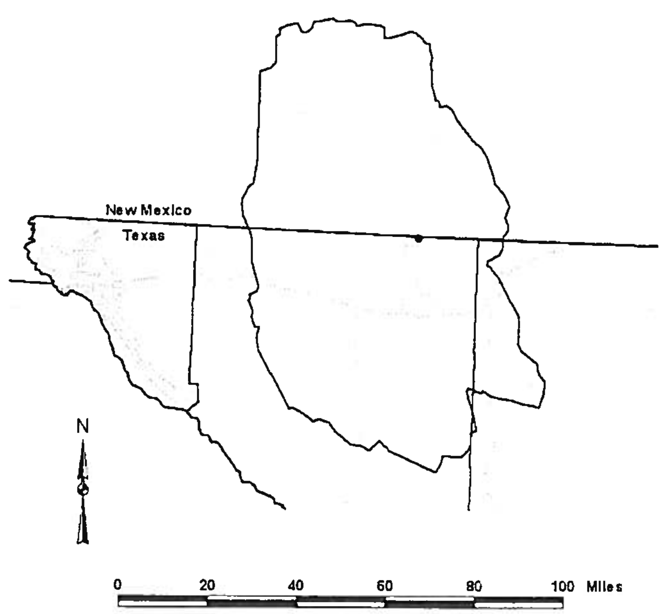
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

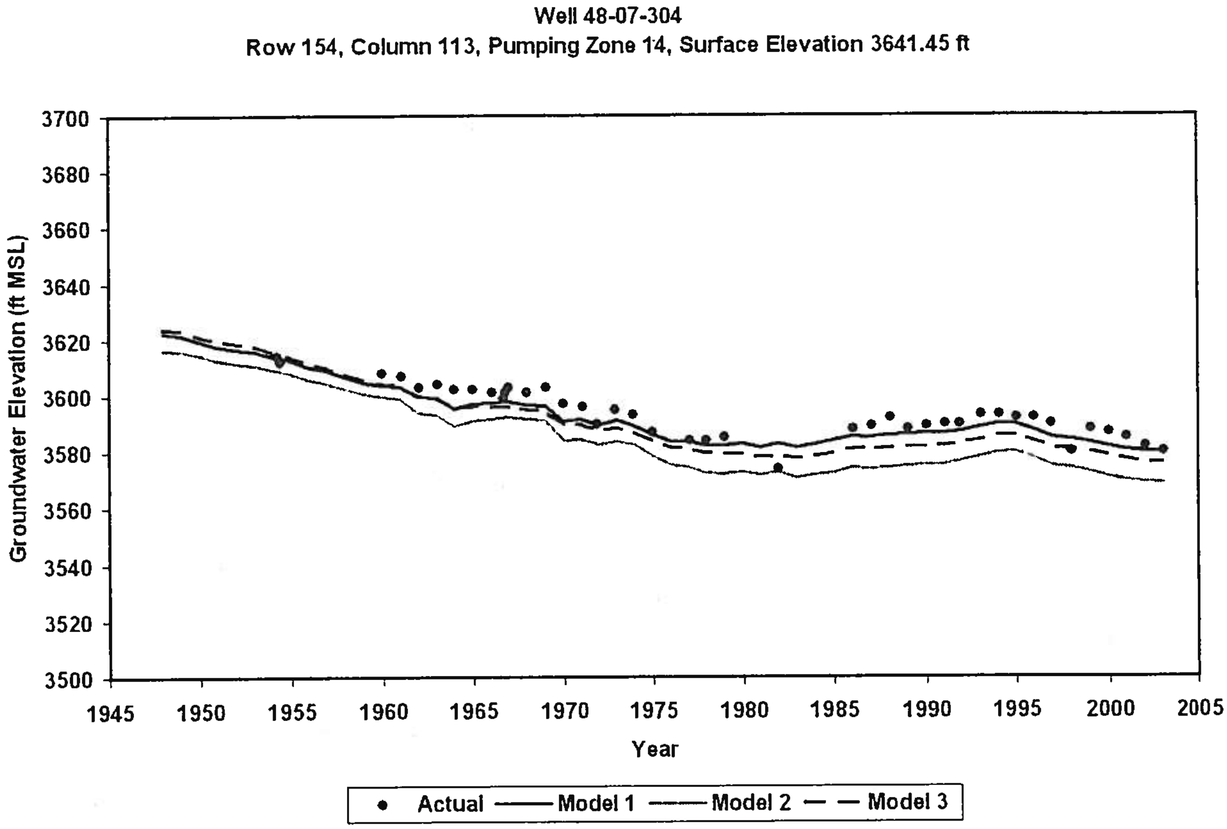


Well 48-07-301
Row 148, Column 113, Pumping Zone 13, Surface Elevation 3703.94 ft



Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2





Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
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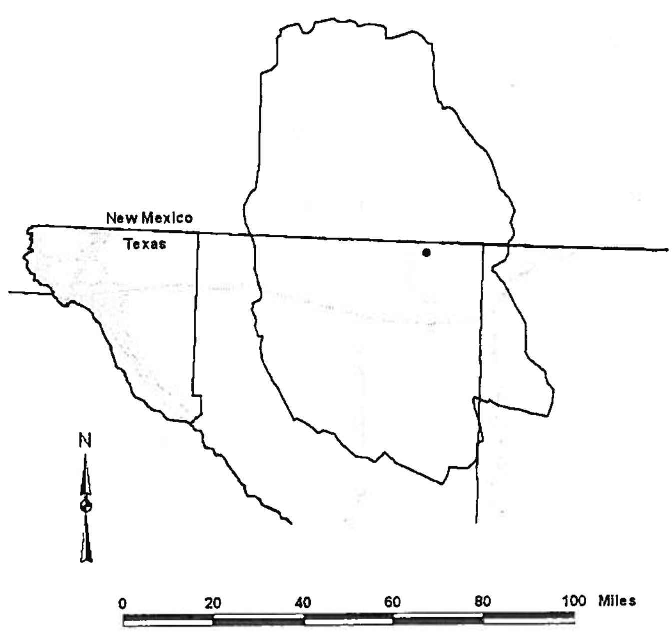
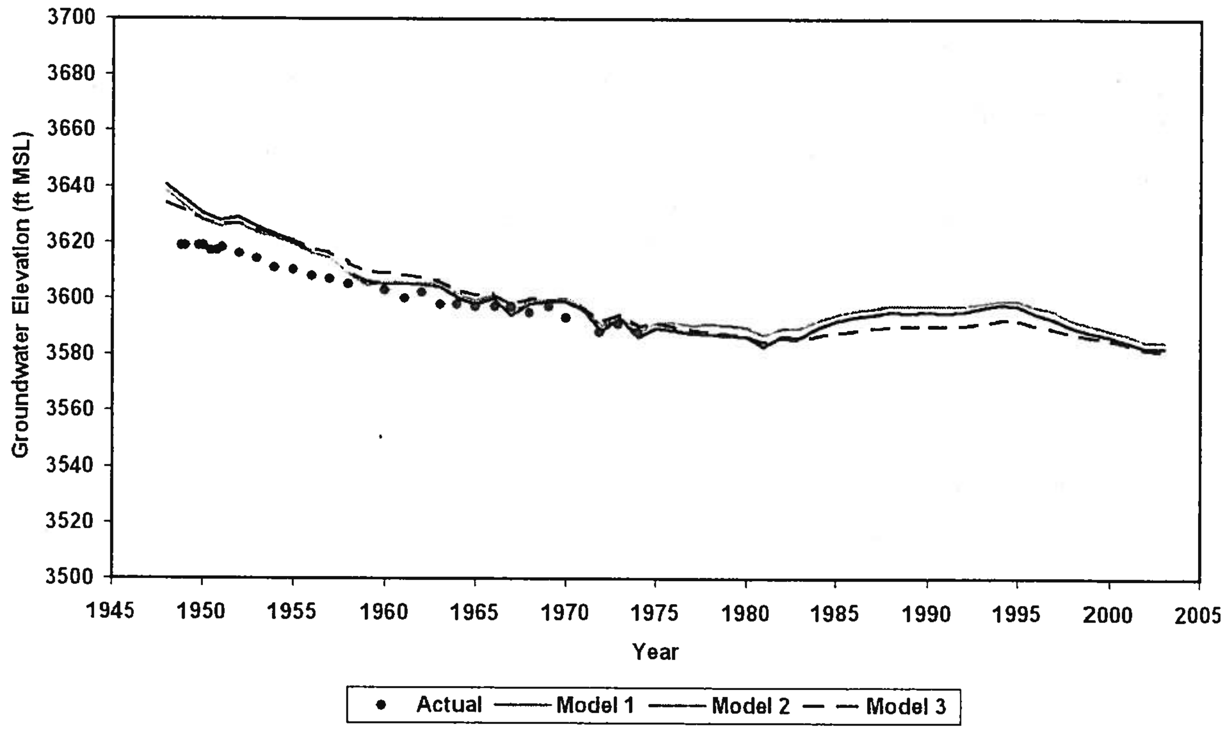
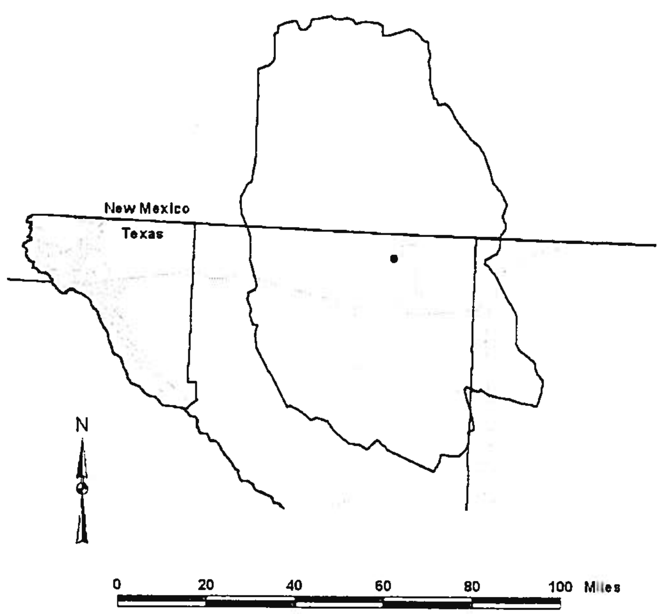


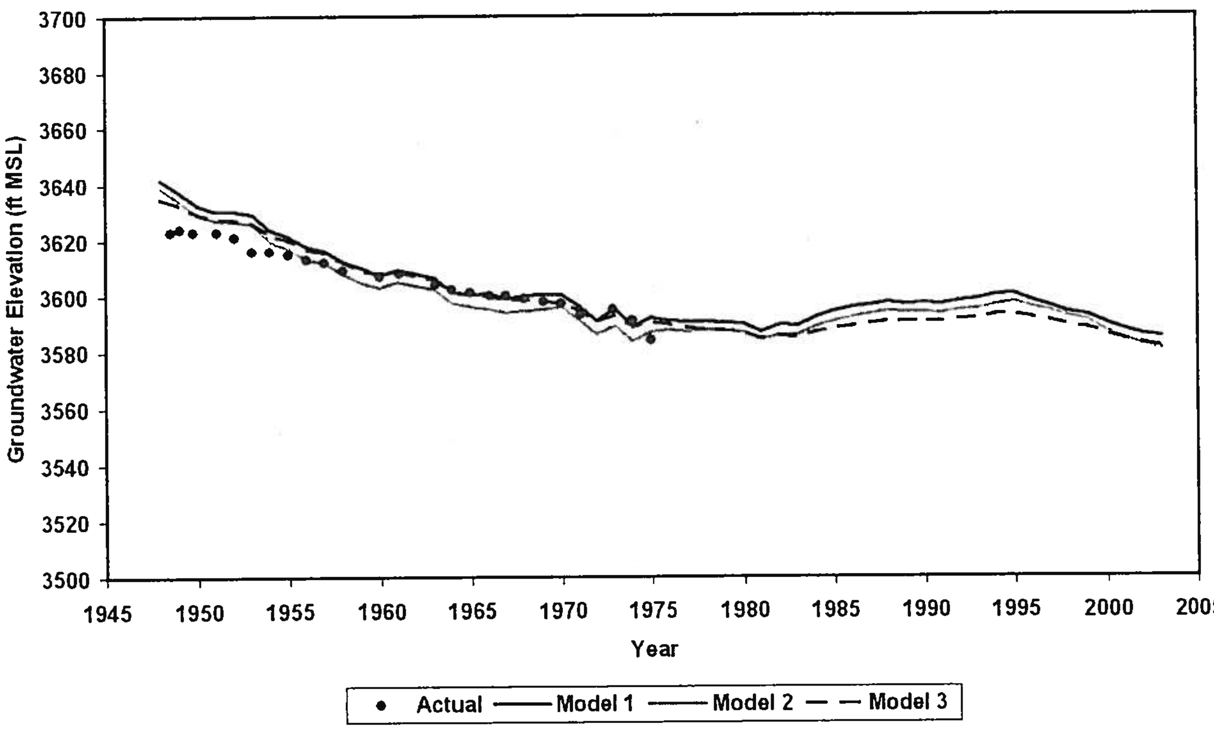
Well 48-07-402
Row 155, Column 96, Pumping Zone 11, Surface Elevation 3720.23 ft



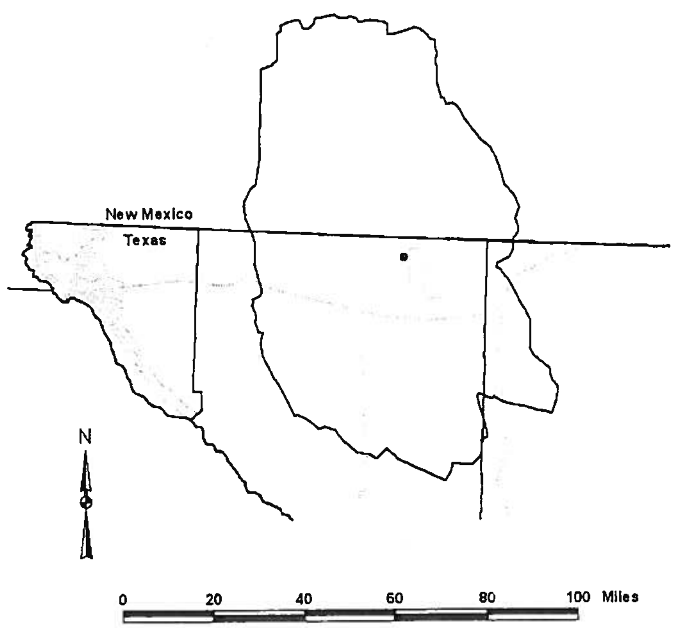
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



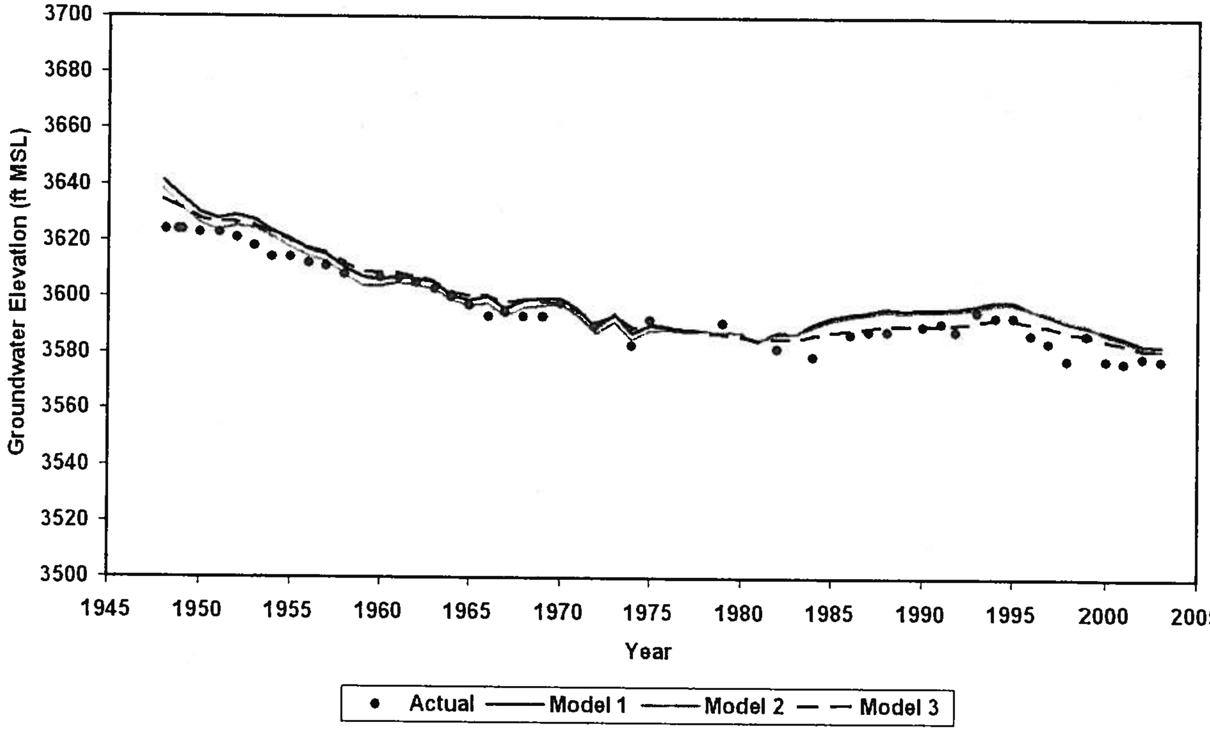
Well 48-07-403
Row 151, Column 100, Pumping Zone 9, Surface Elevation 3711.49 ft



Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



Well 48-07-405
Row 153, Column 98, Pumping Zone 12, Surface Elevation 3715.75 ft



Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
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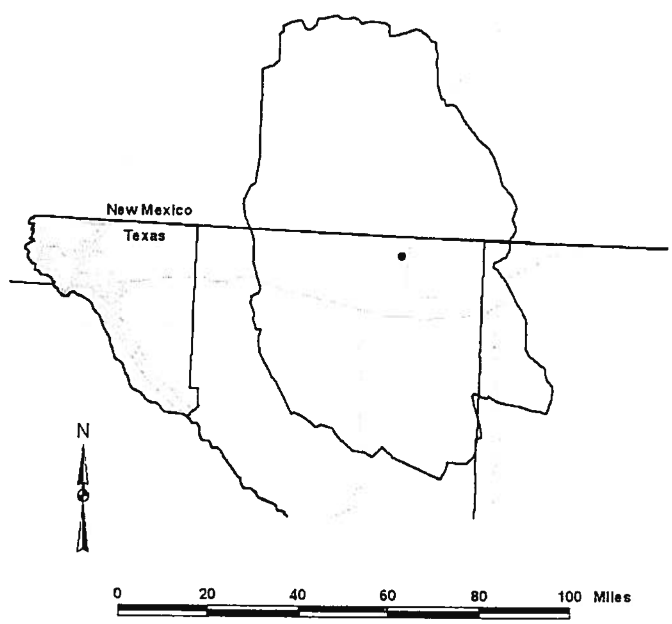
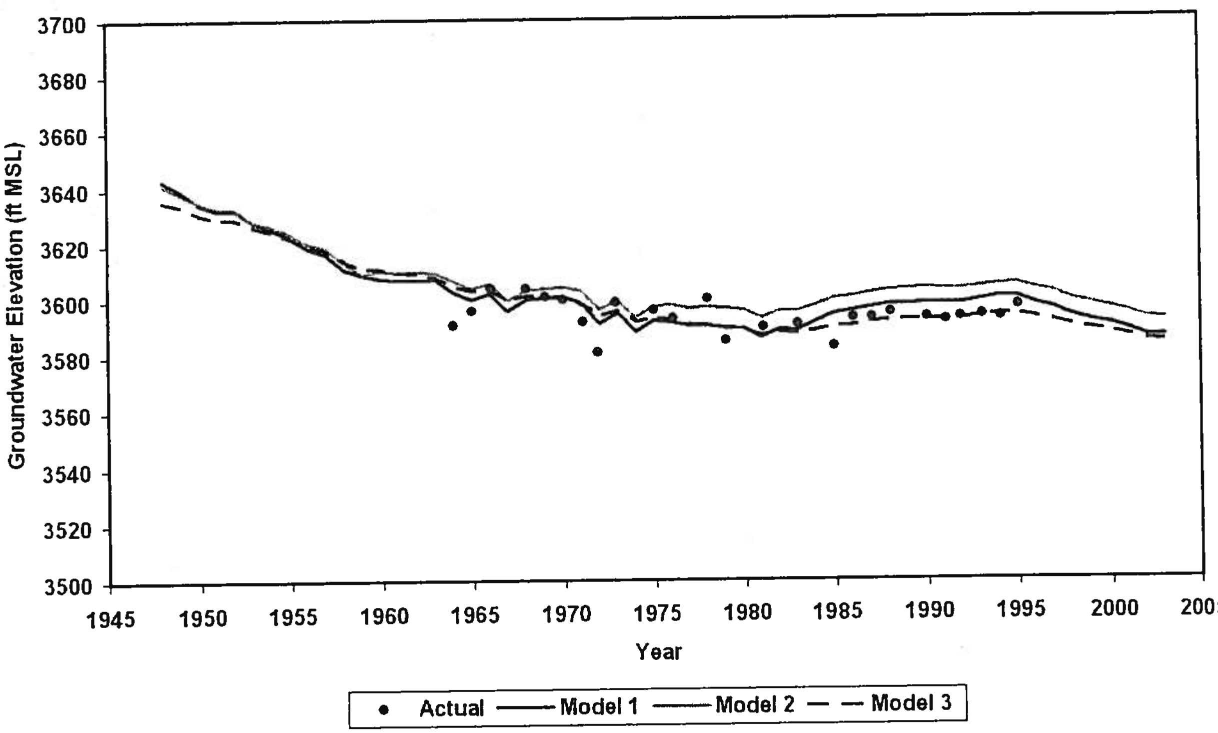
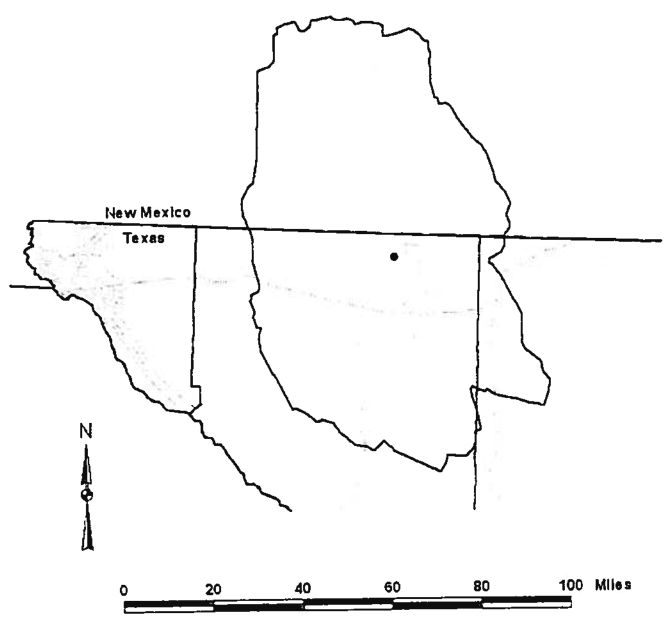


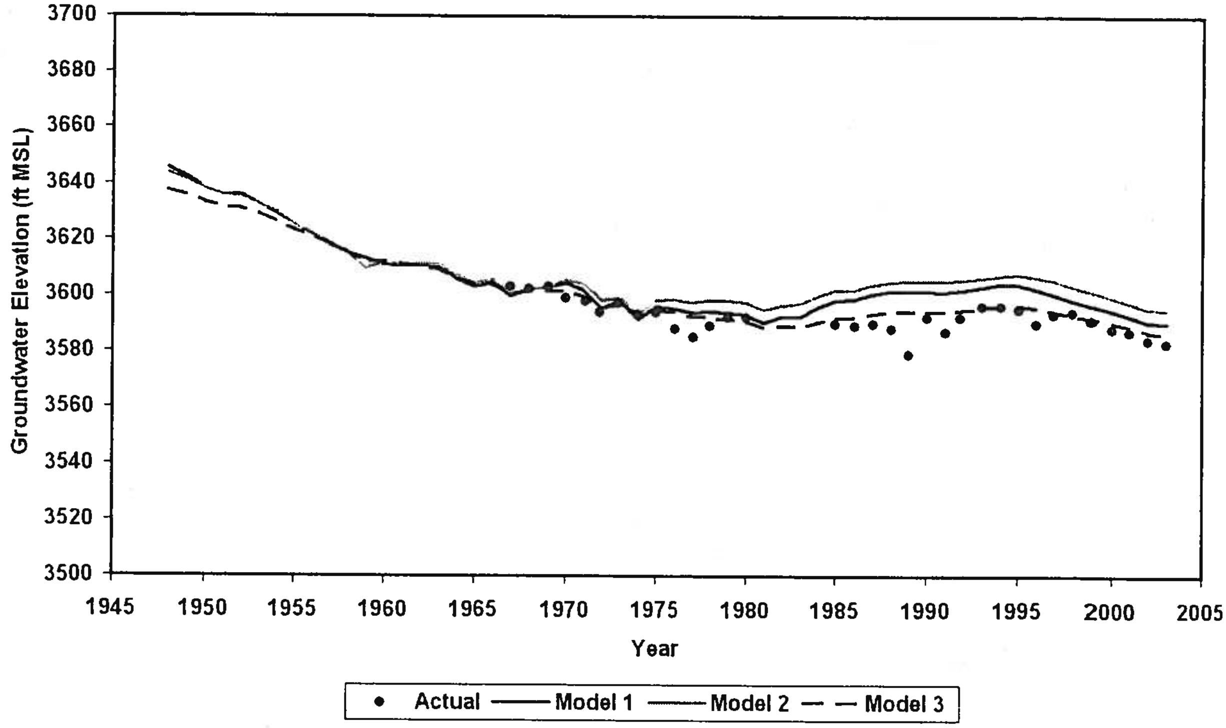
Well 48-07-414
Row 154, Column 94, Pumping Zone 11, Surface Elevation 3748.83 ft



Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



Well 48-07-418
Row 151, Column 95, Pumping Zone 7, Surface Elevation 3766.36 ft



Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
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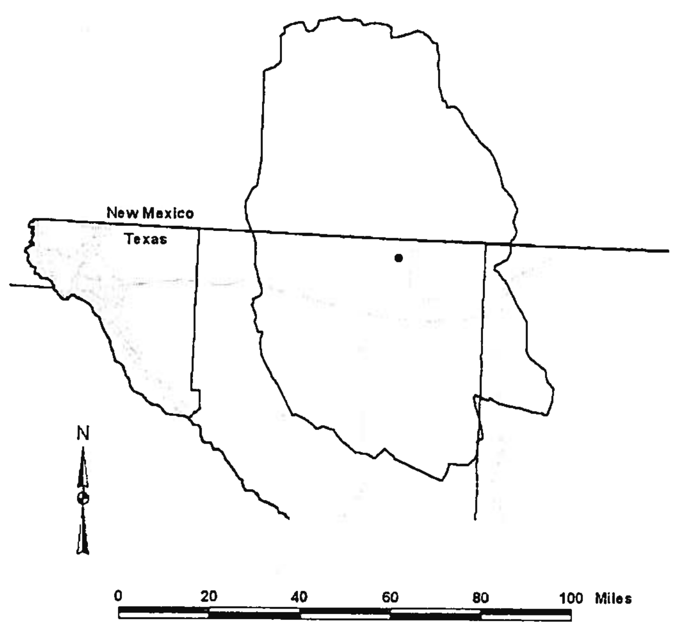
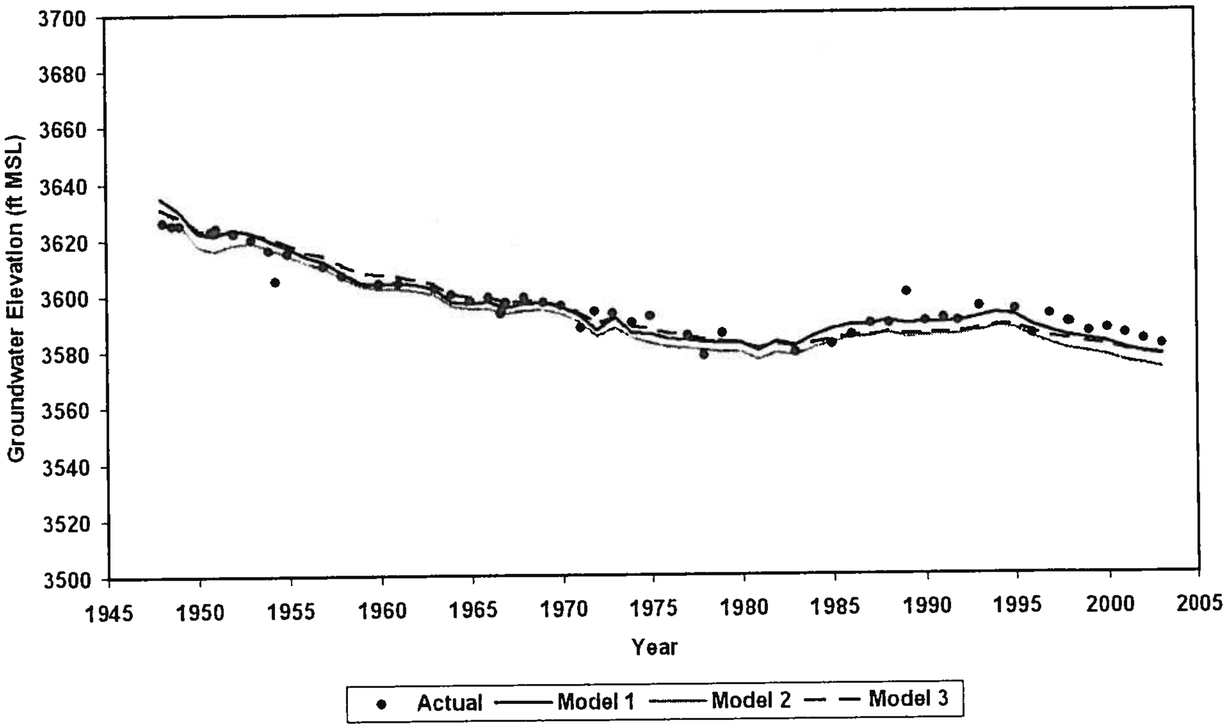
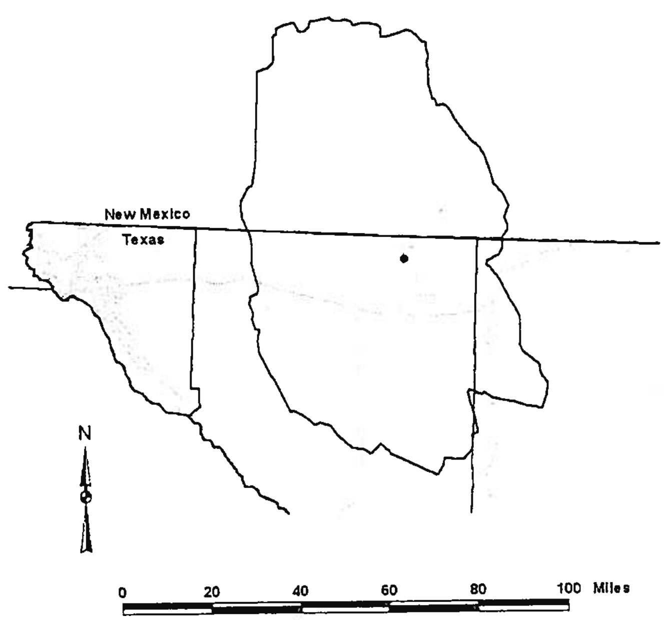


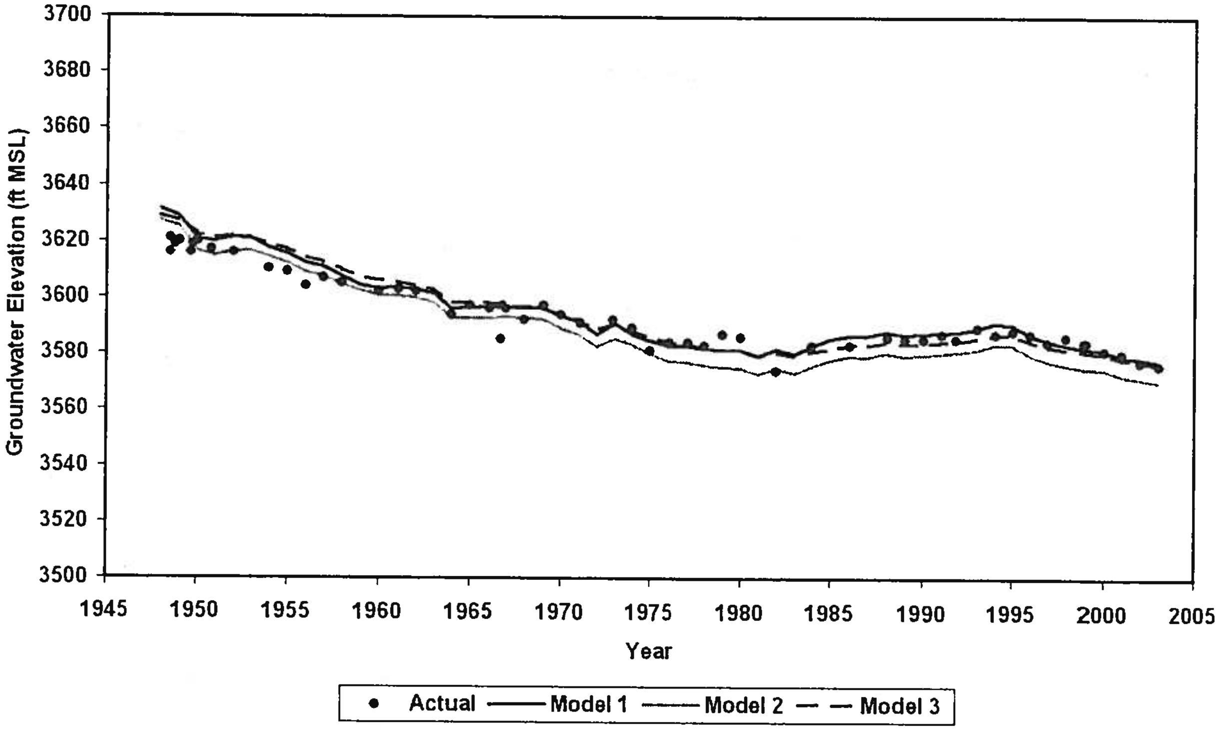
Well 48-07-501
Row 156, Column 101, Pumping Zone 15, Surface Elevation 3673.57 ft



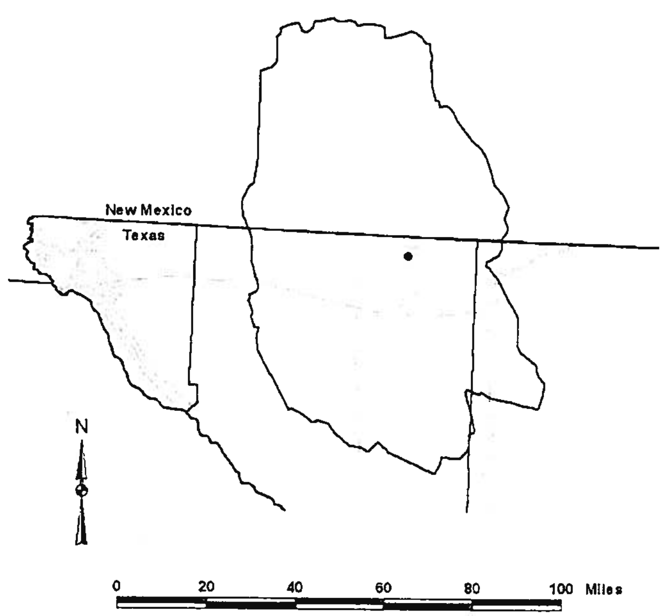
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

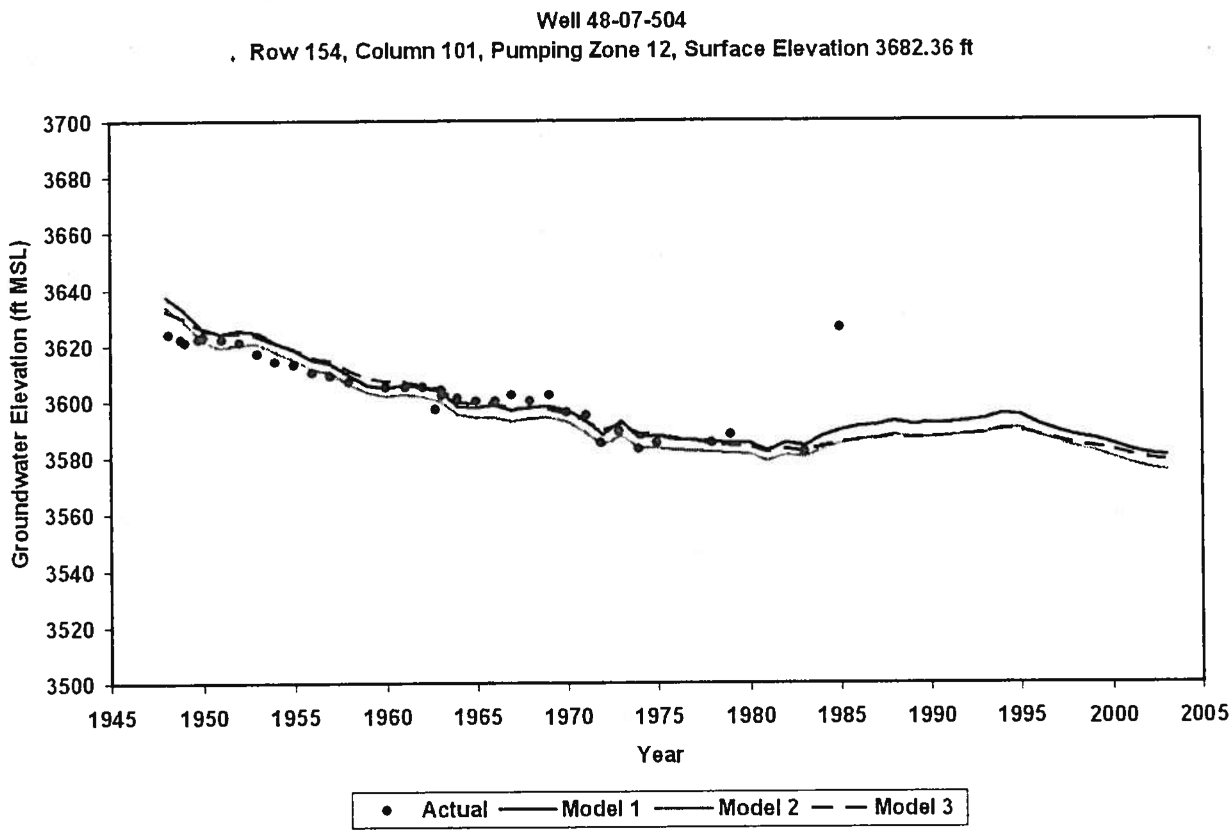


Well 48-07-502
Row 156, Column 104, Pumping Zone 15, Surface Elevation 3648.21 ft



Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2





Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
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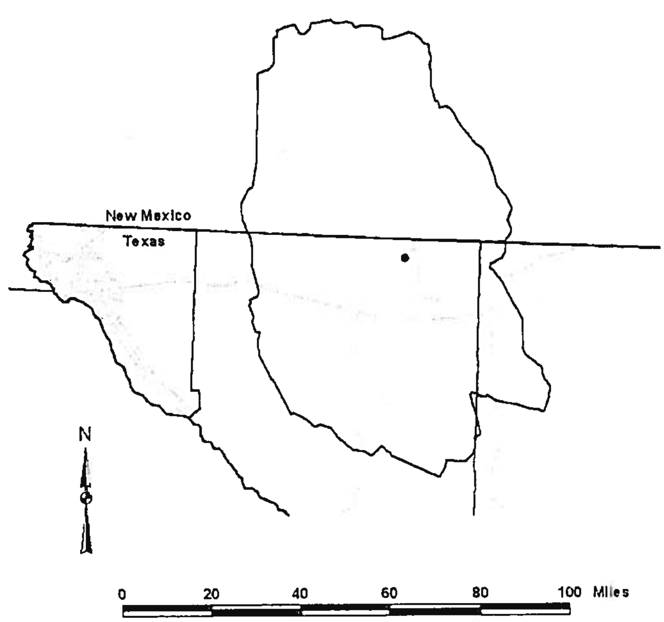
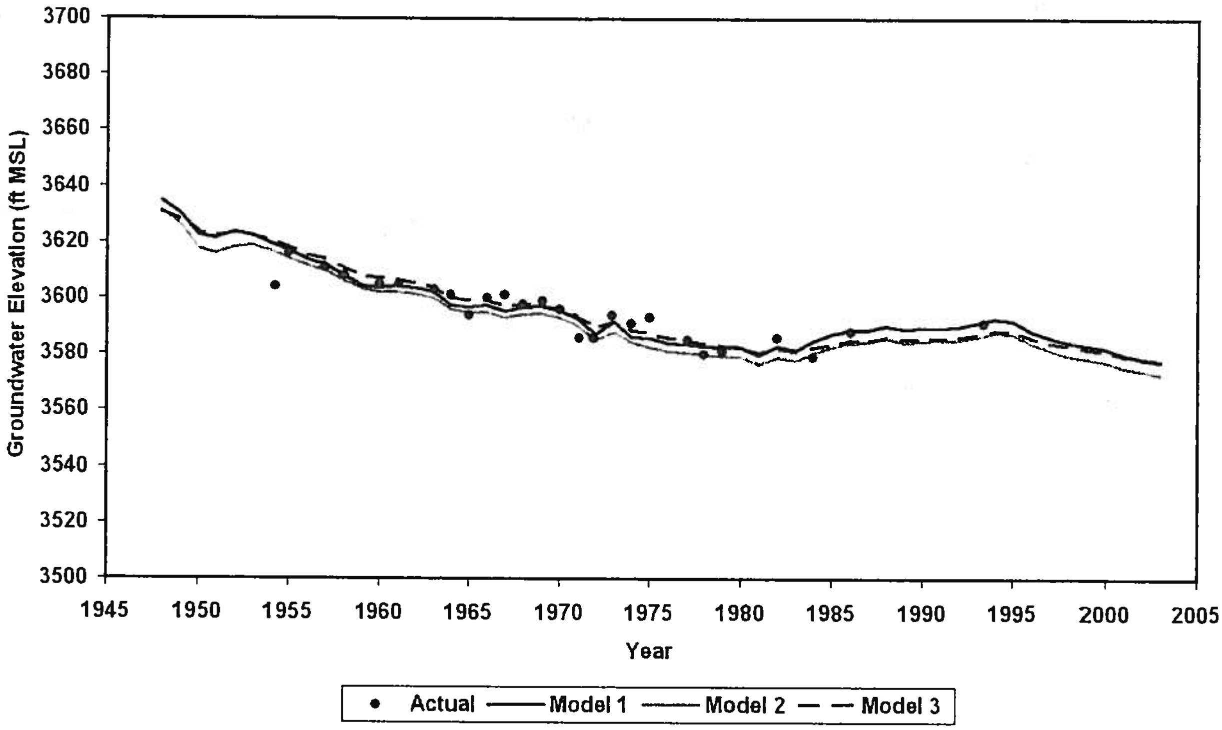
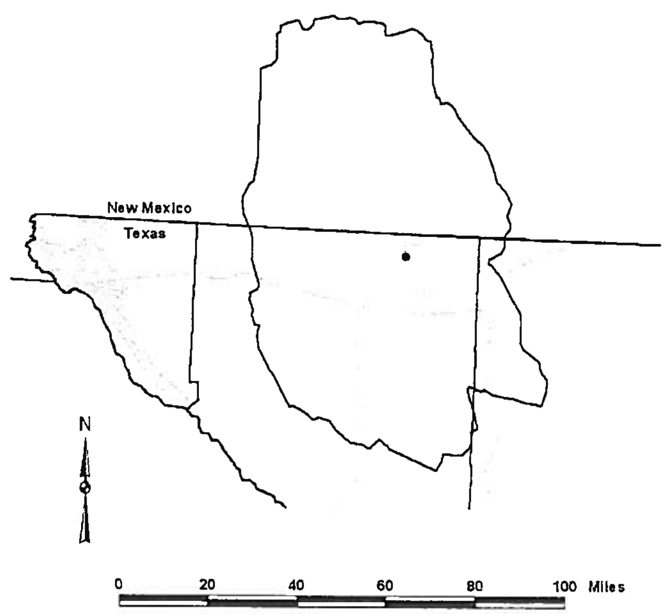


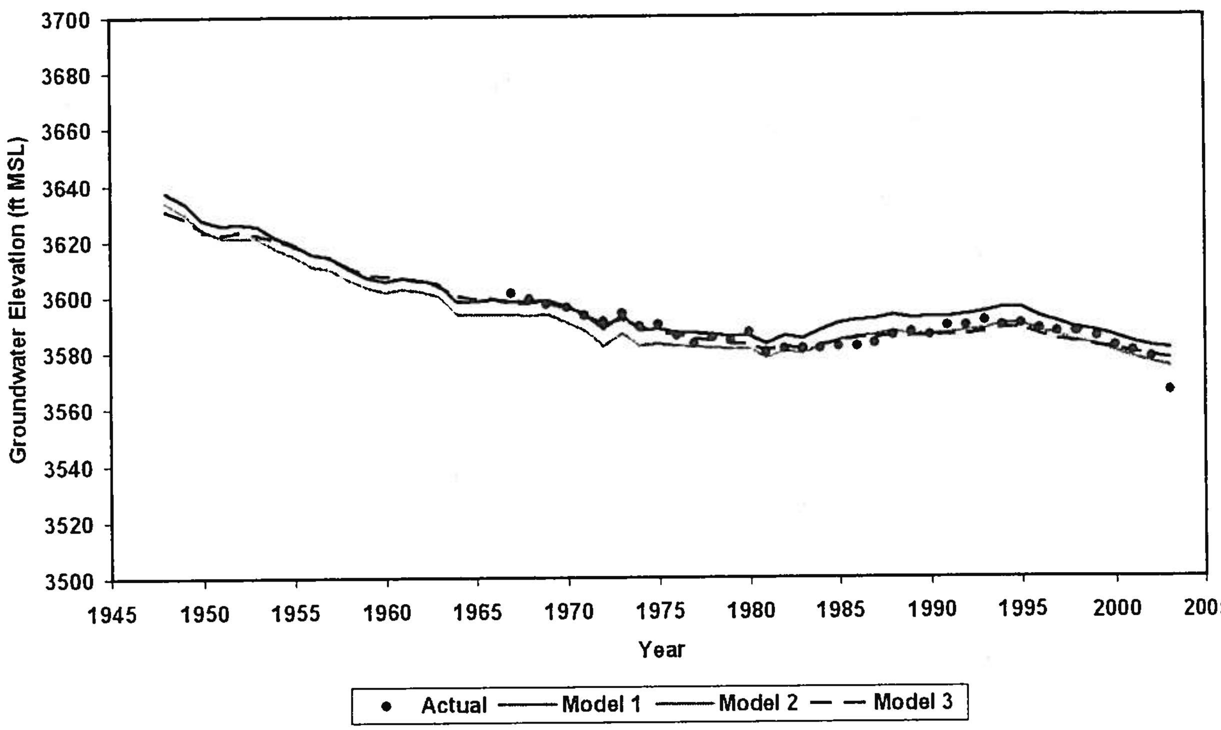
Well 48-07-505
Row 156, Column 101, Pumping Zone 15, Surface Elevation 3673.57 ft



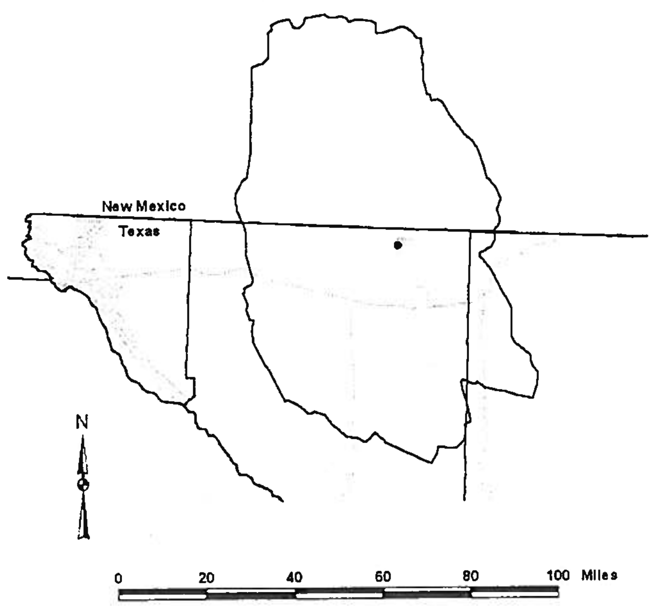
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

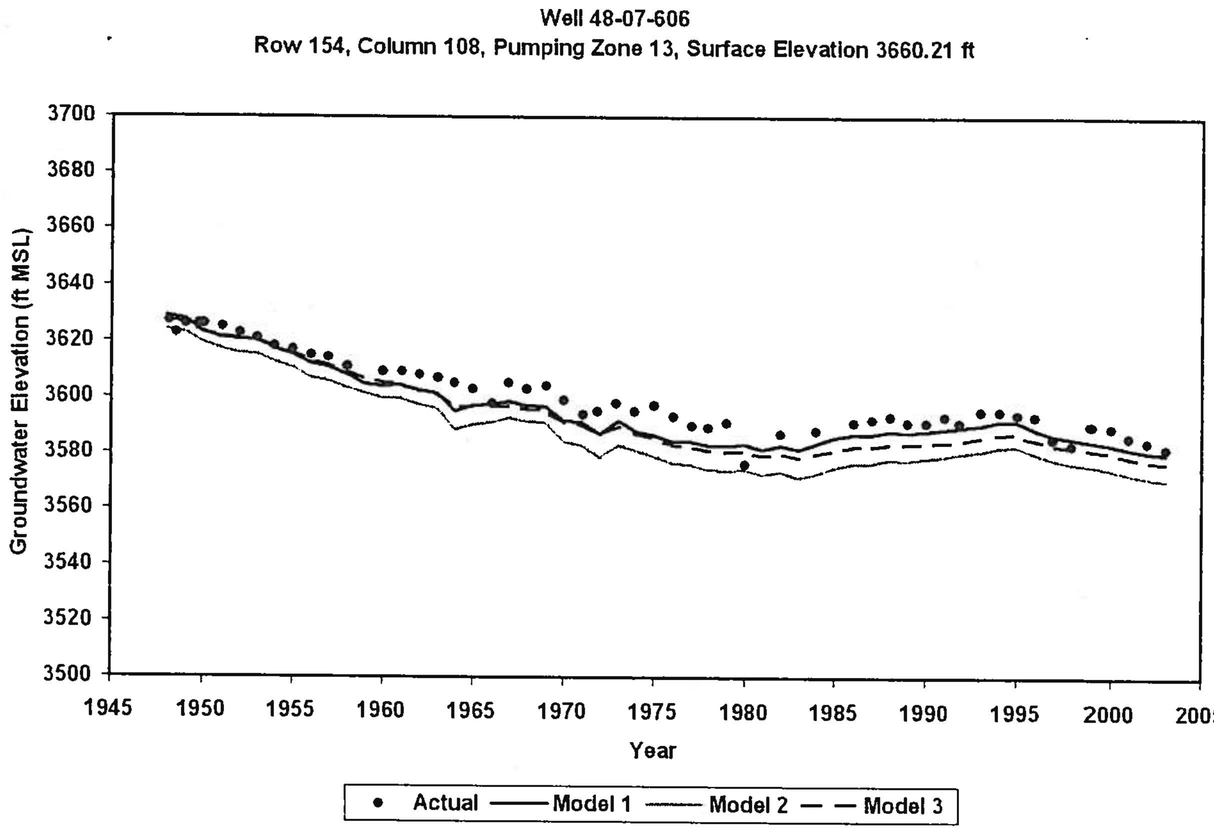


Well 48-07-516
Row 153, Column 102, Pumping Zone 13, Surface Elevation 3678.30 ft

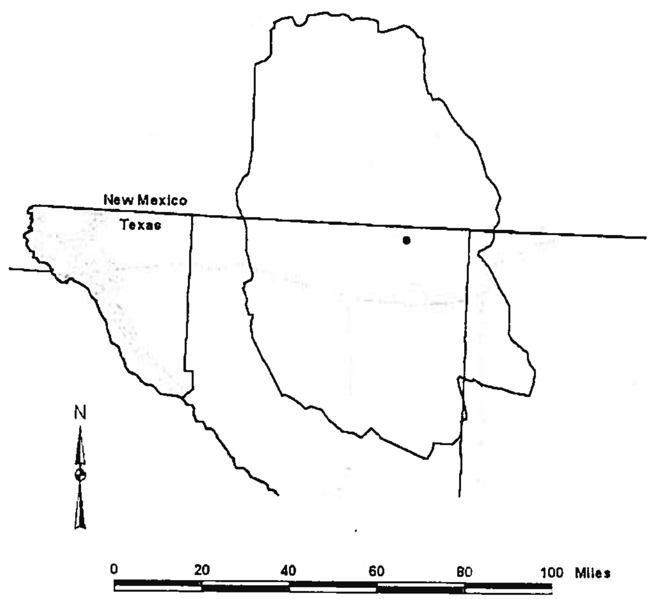


Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

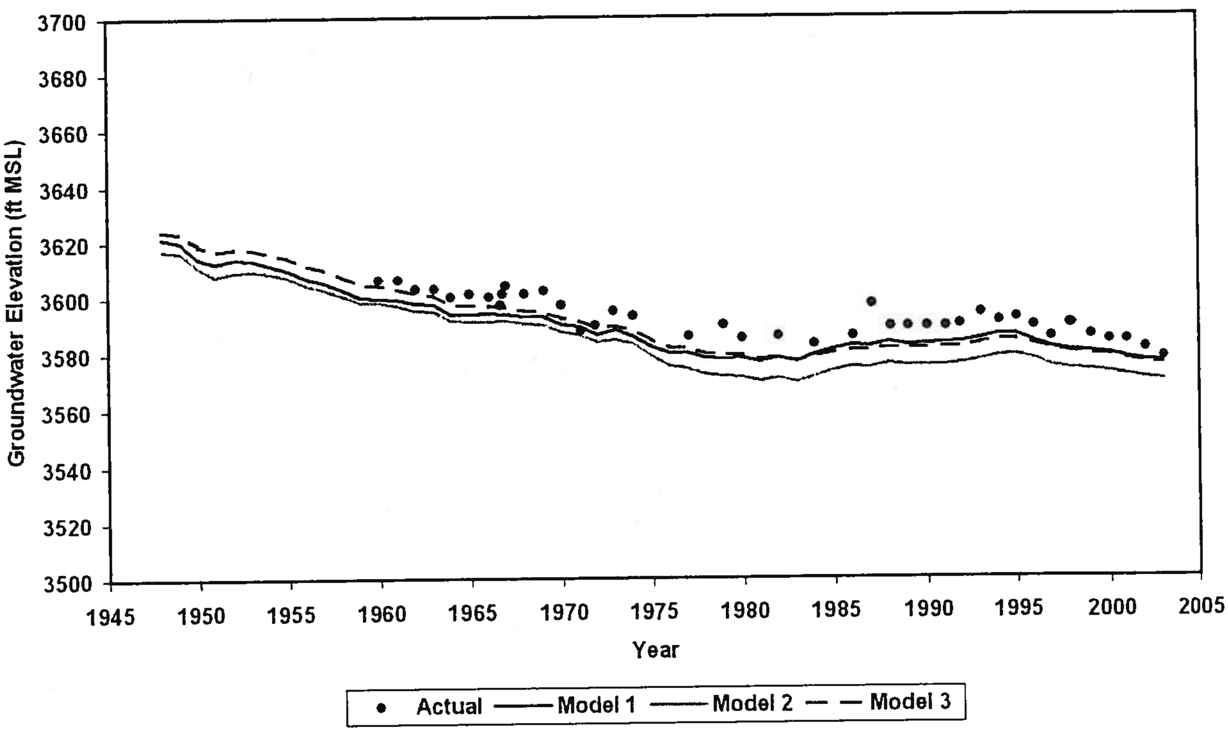




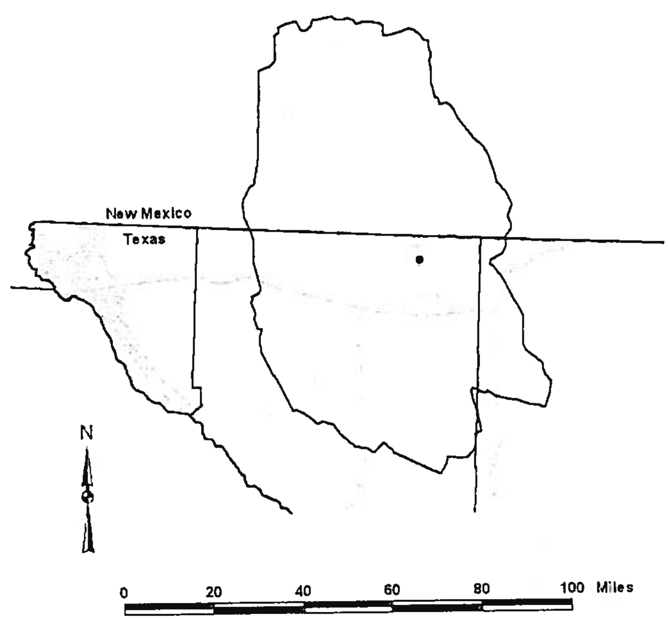
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



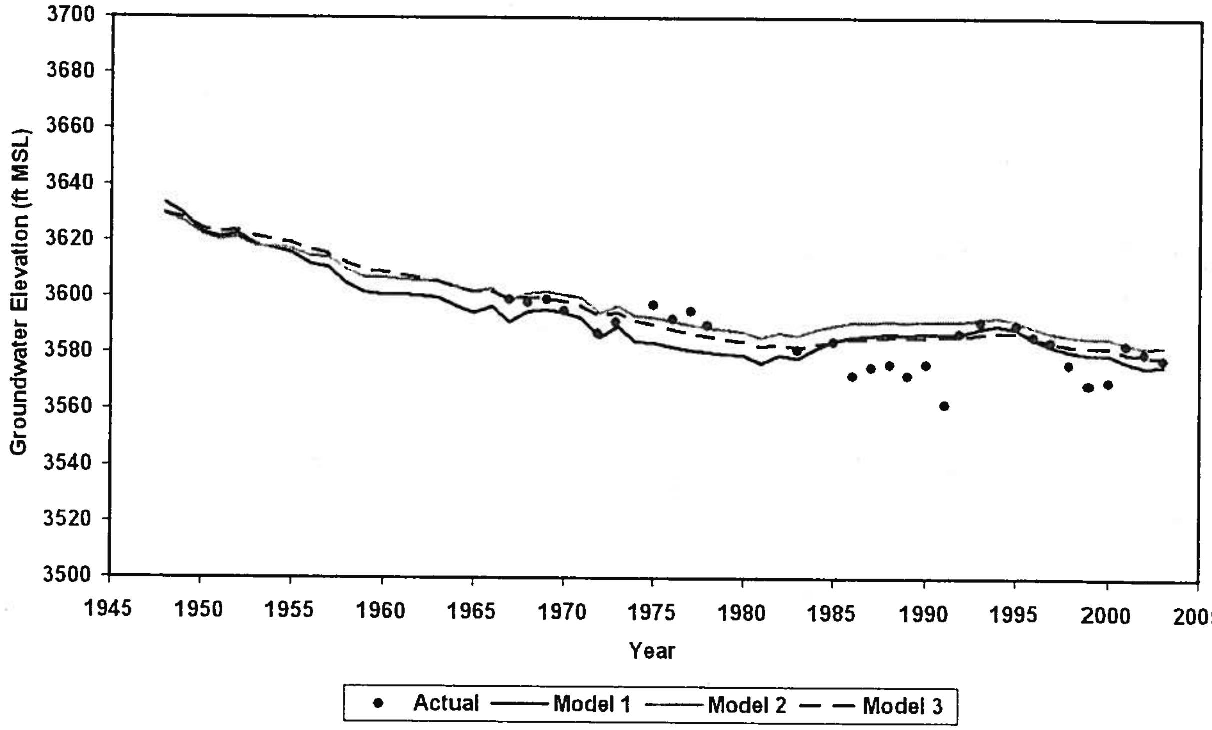
Well 48-07-607
Row 160, Column 108, Pumping Zone 16, Surface Elevation 3634.32 ft



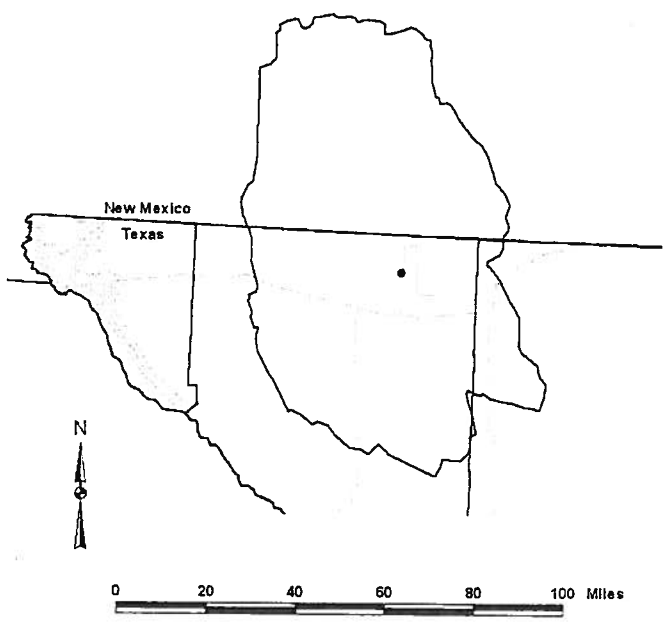
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

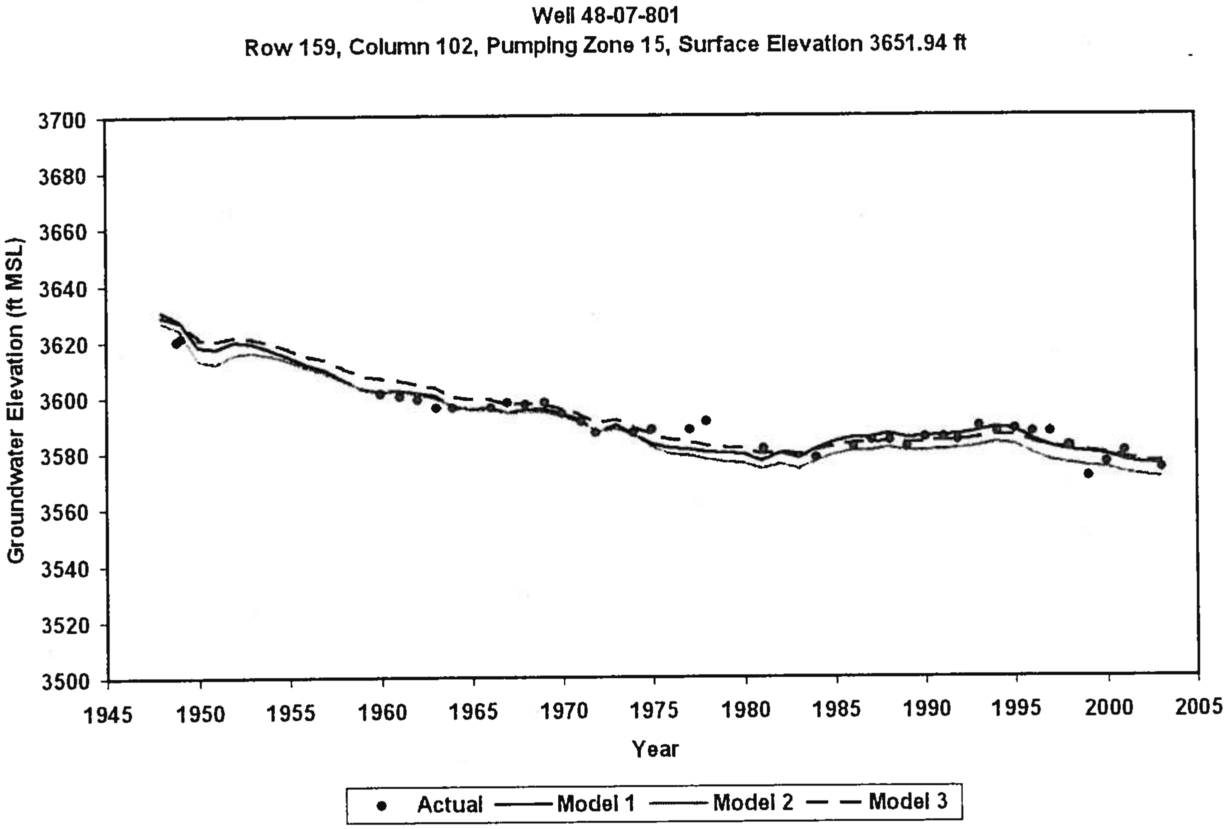


Well 48-07-708
Row 164, Column 96, Pumping Zone 11, Surface Elevation 3711.98 ft

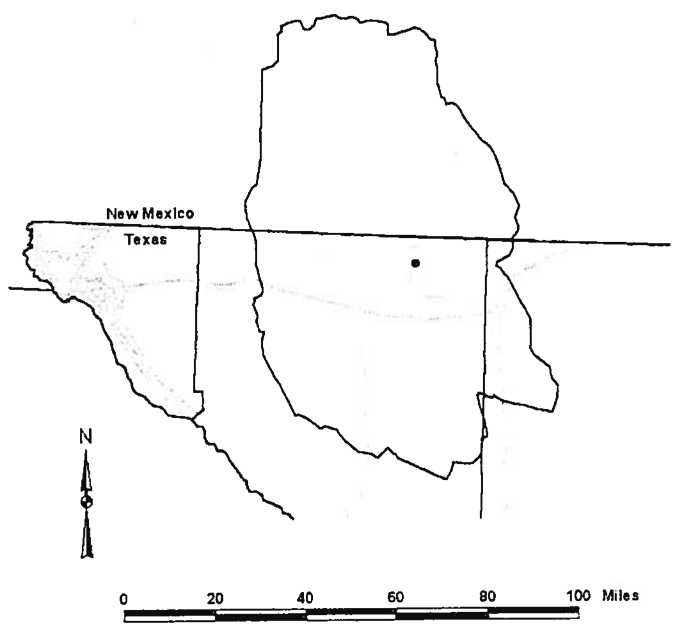


Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

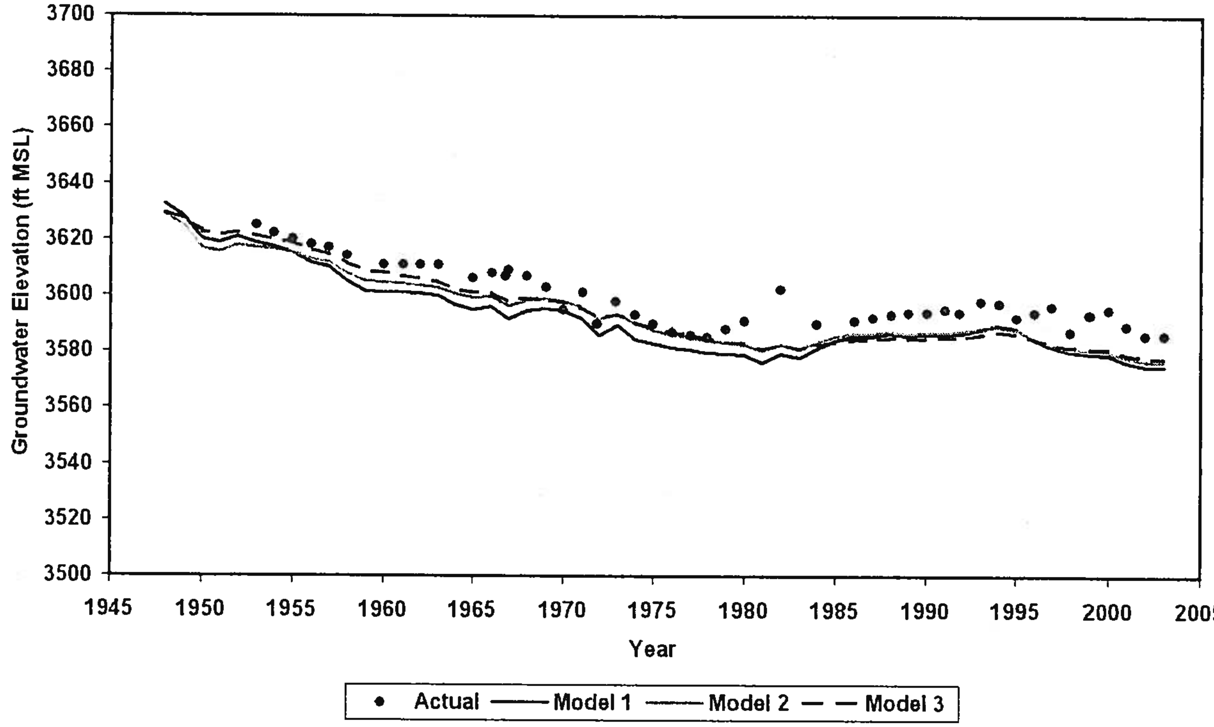




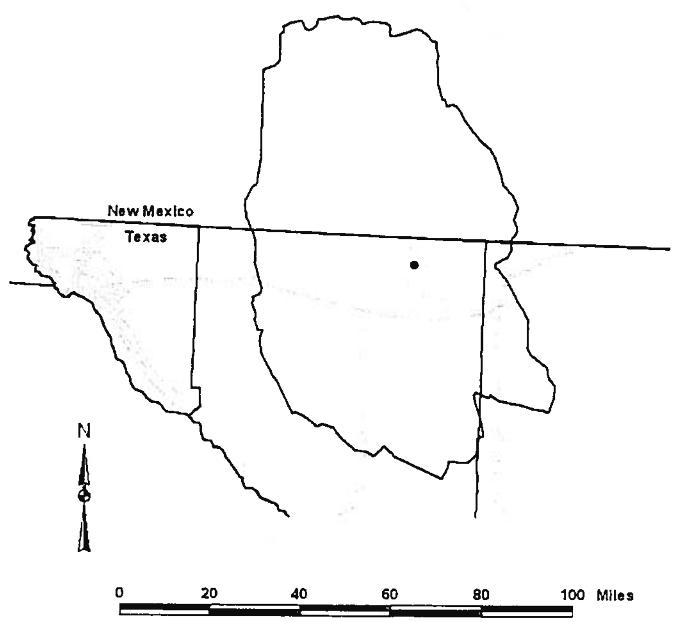
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



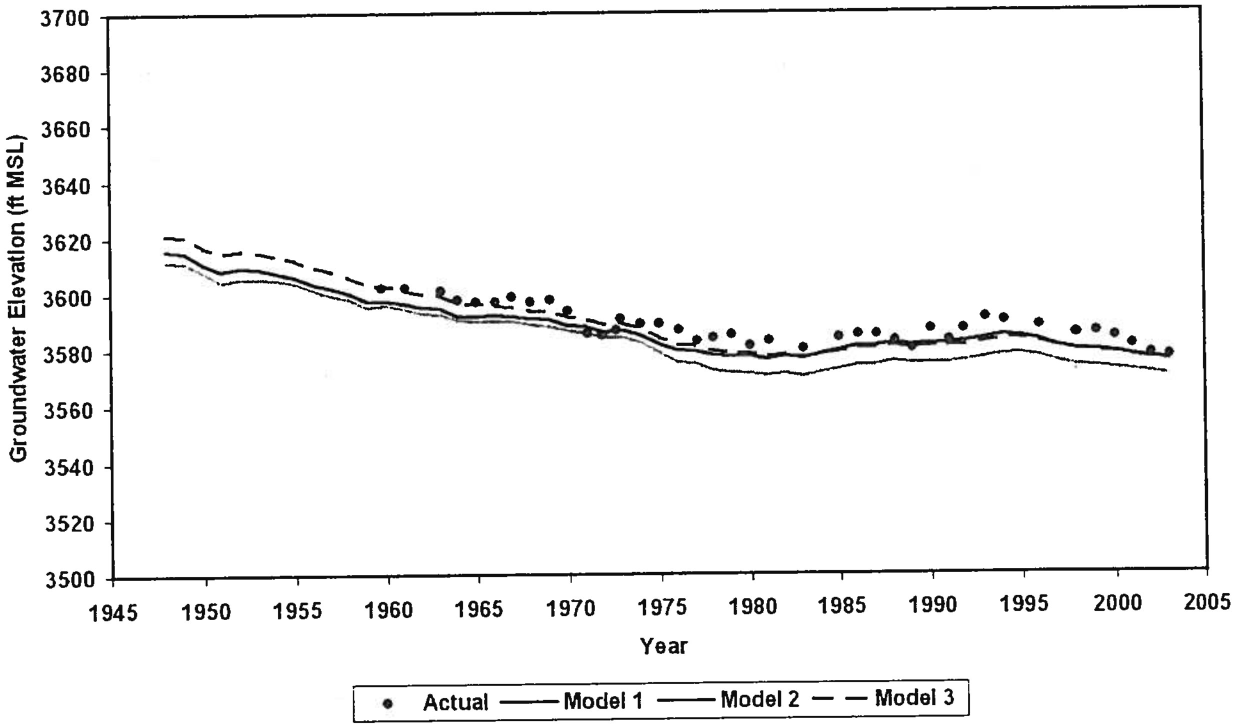
Well 48-07-803
Row 162, Column 98, Pumping Zone 15, Surface Elevation 3691.00 ft



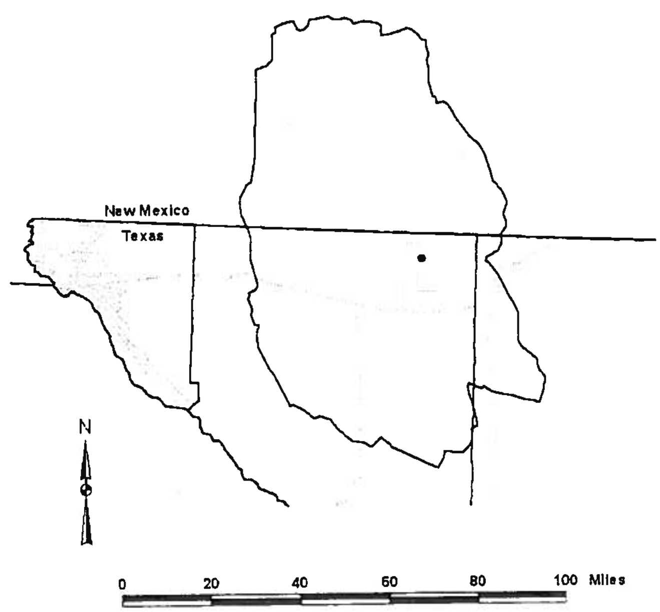
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



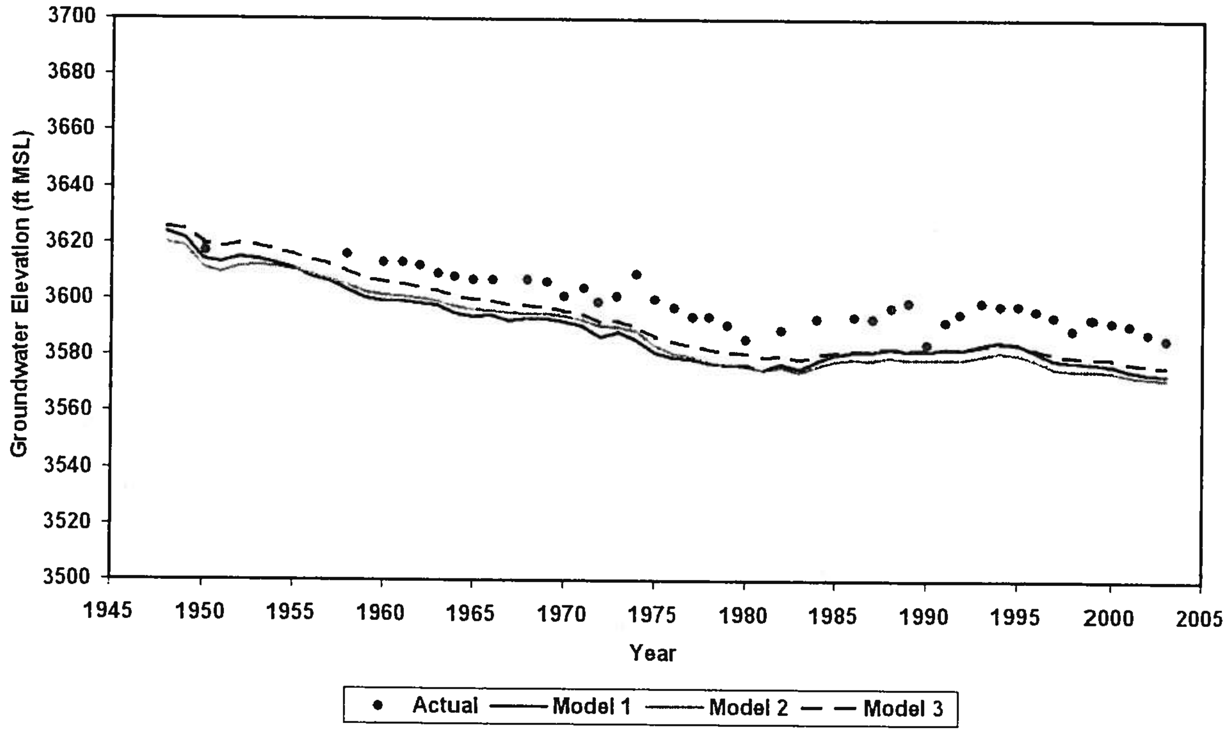
Well 48-07-901
Row 162, Column 110, Pumping Zone 16, Surface Elevation 3615.98 ft



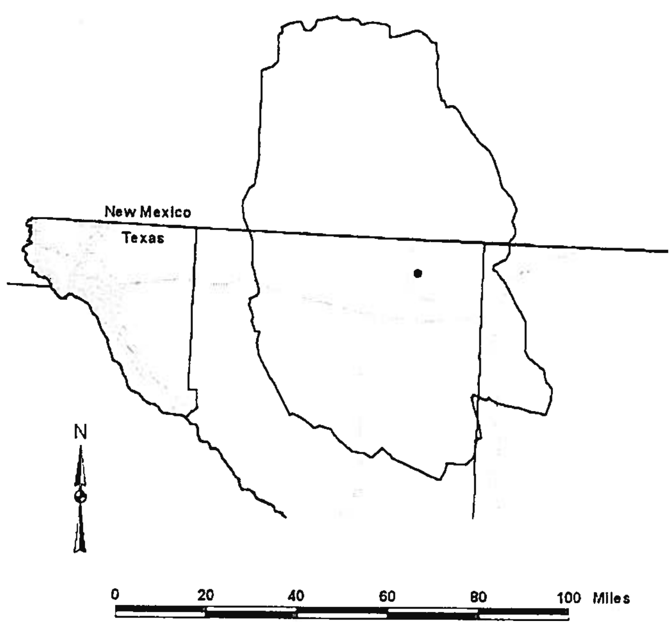
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



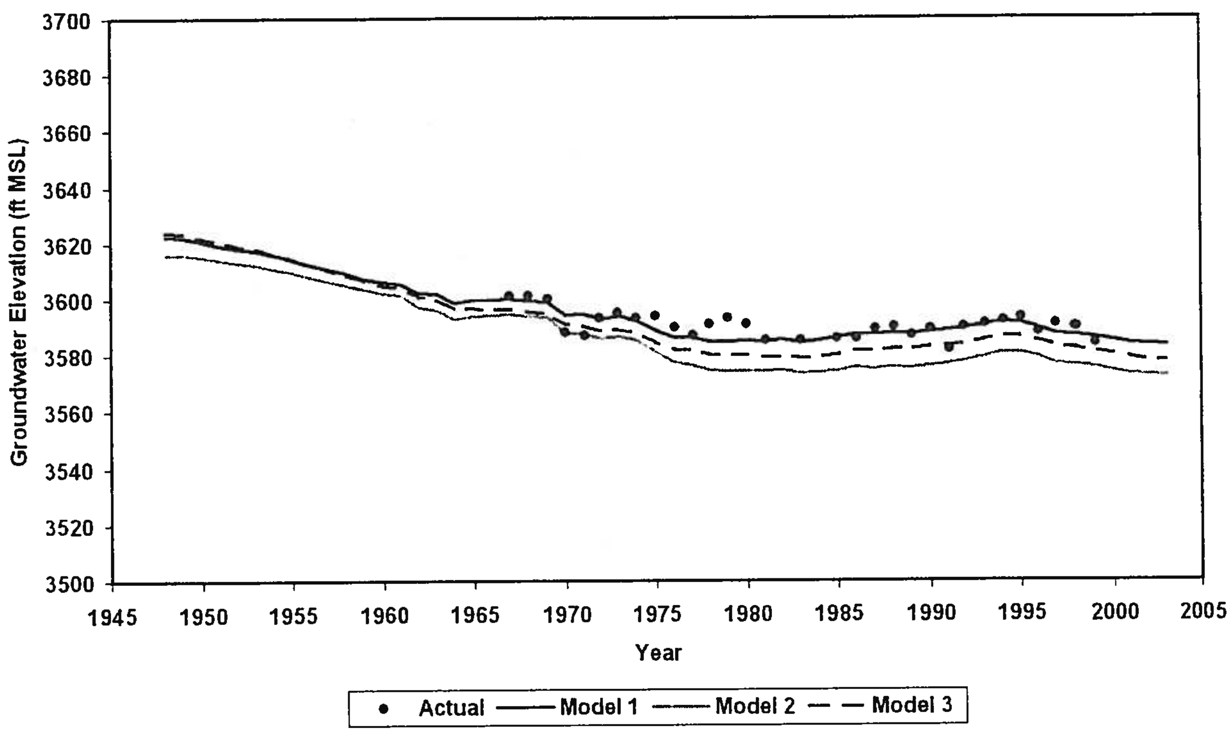
Well 48-07-904
Row 164, Column 103, Pumping Zone 15, Surface Elevation 3630.72 ft



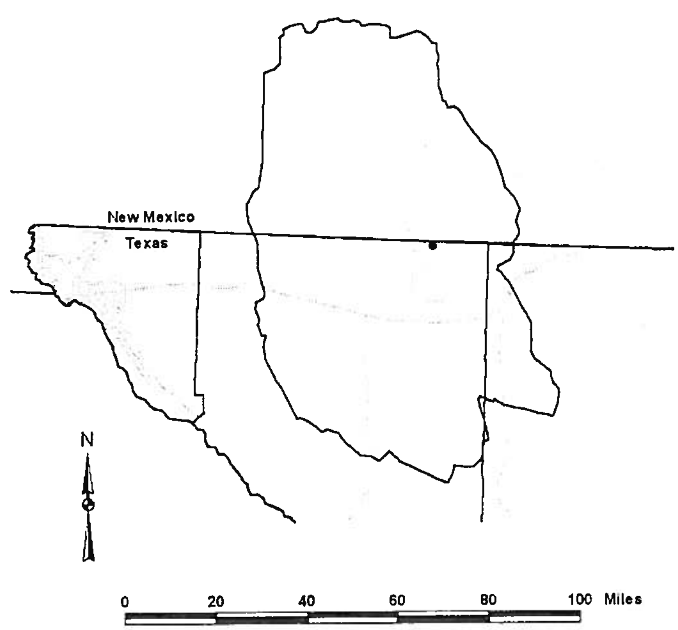
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



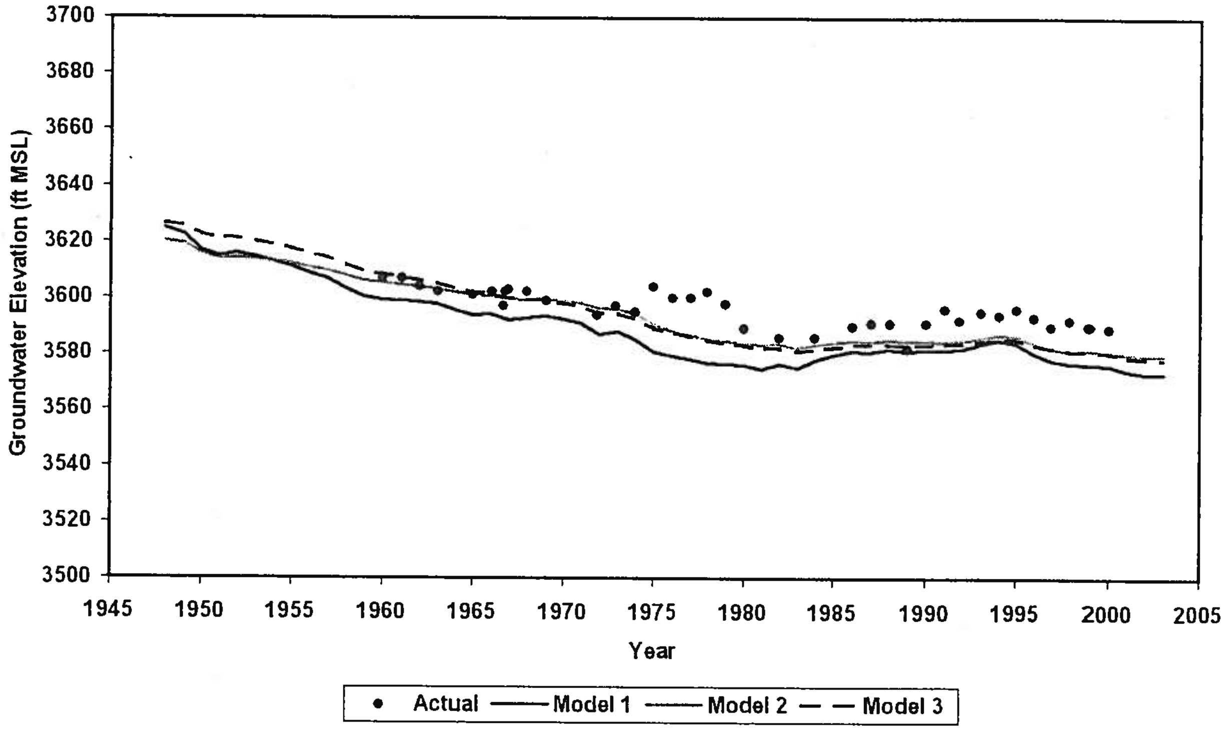
Well 48-08-102
Row 151, Column 116, Pumping Zone 14, Surface Elevation 3646.77 ft



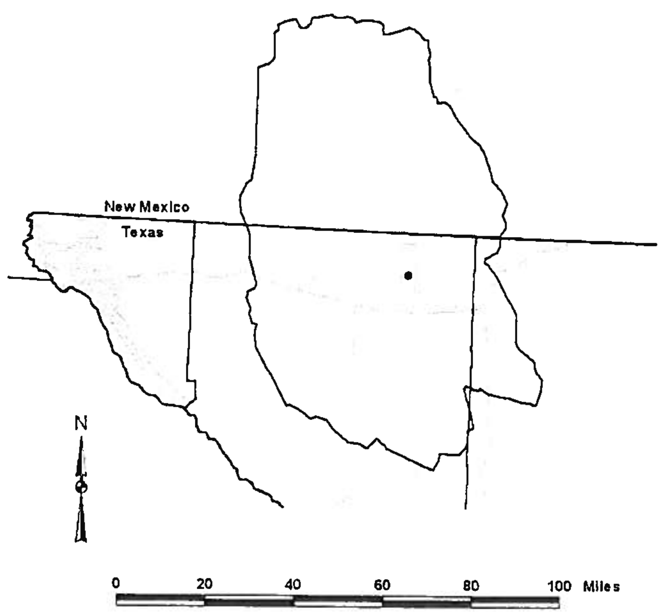
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



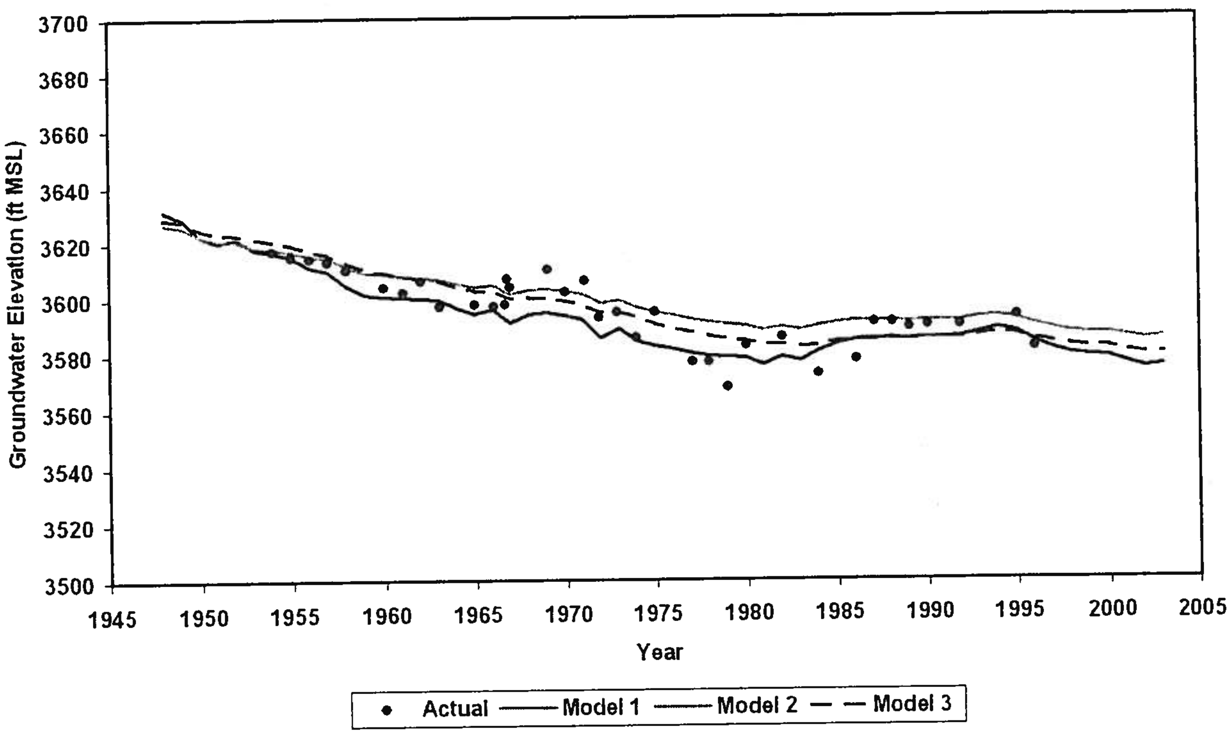
Well 48-15-201
Row 169, Column 100, Pumping Zone 17, Surface Elevation 3632.61 ft



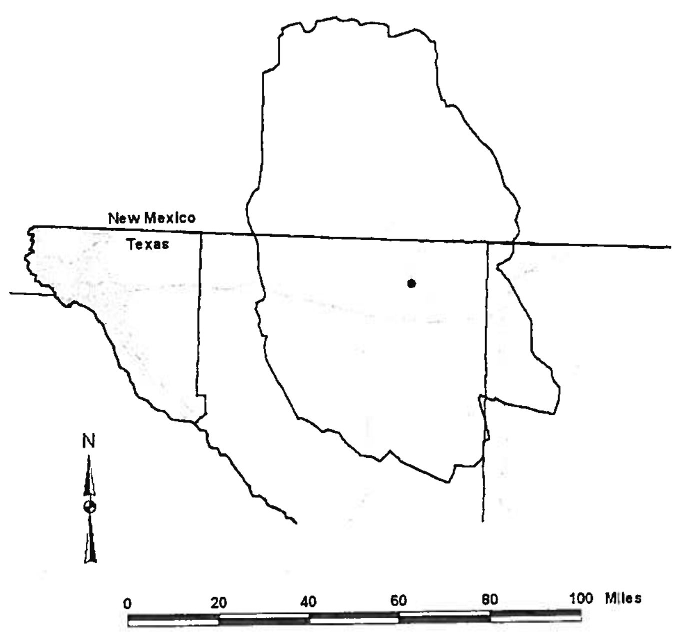
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



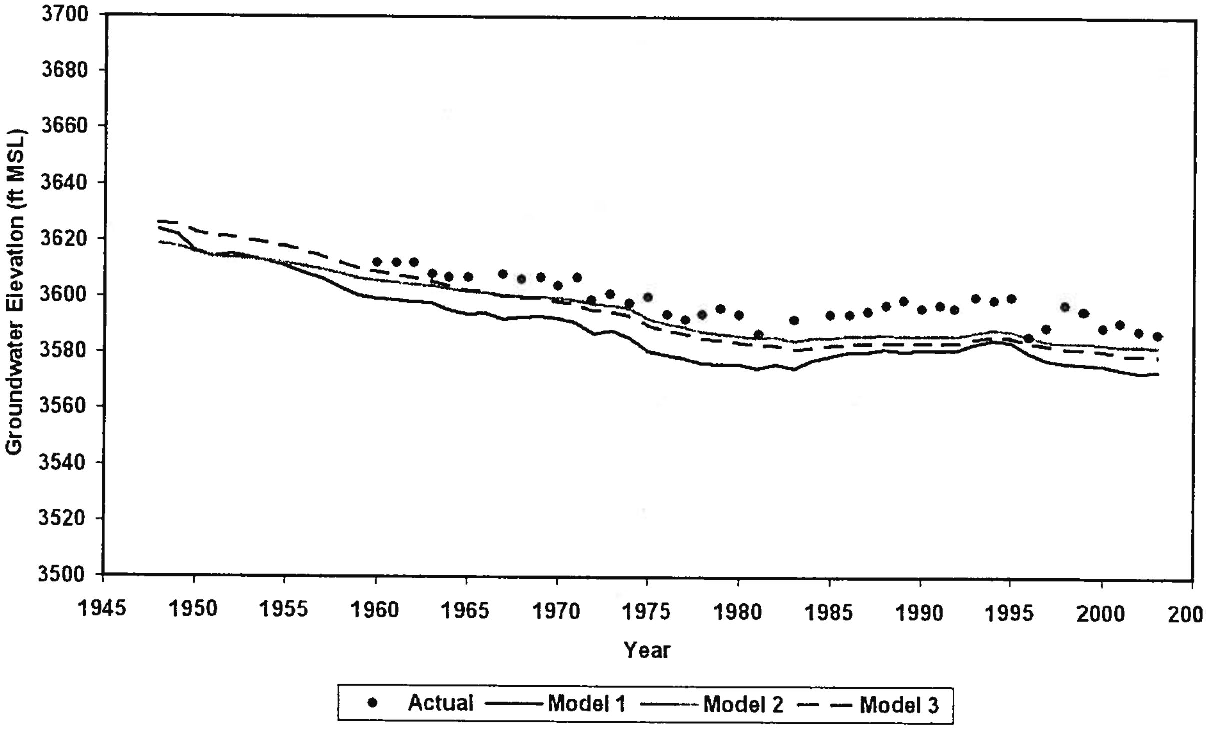
Well 48-15-203
Row 167, Column 96, Pumping Zone 11, Surface Elevation 3695.22 ft



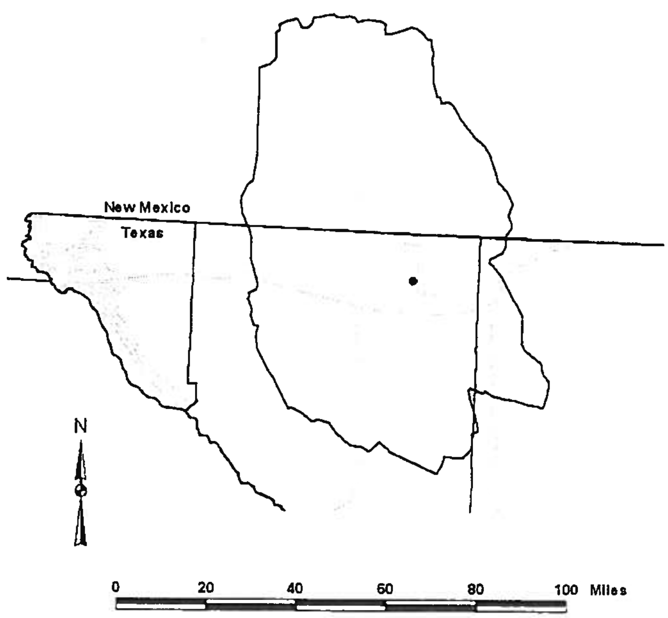
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



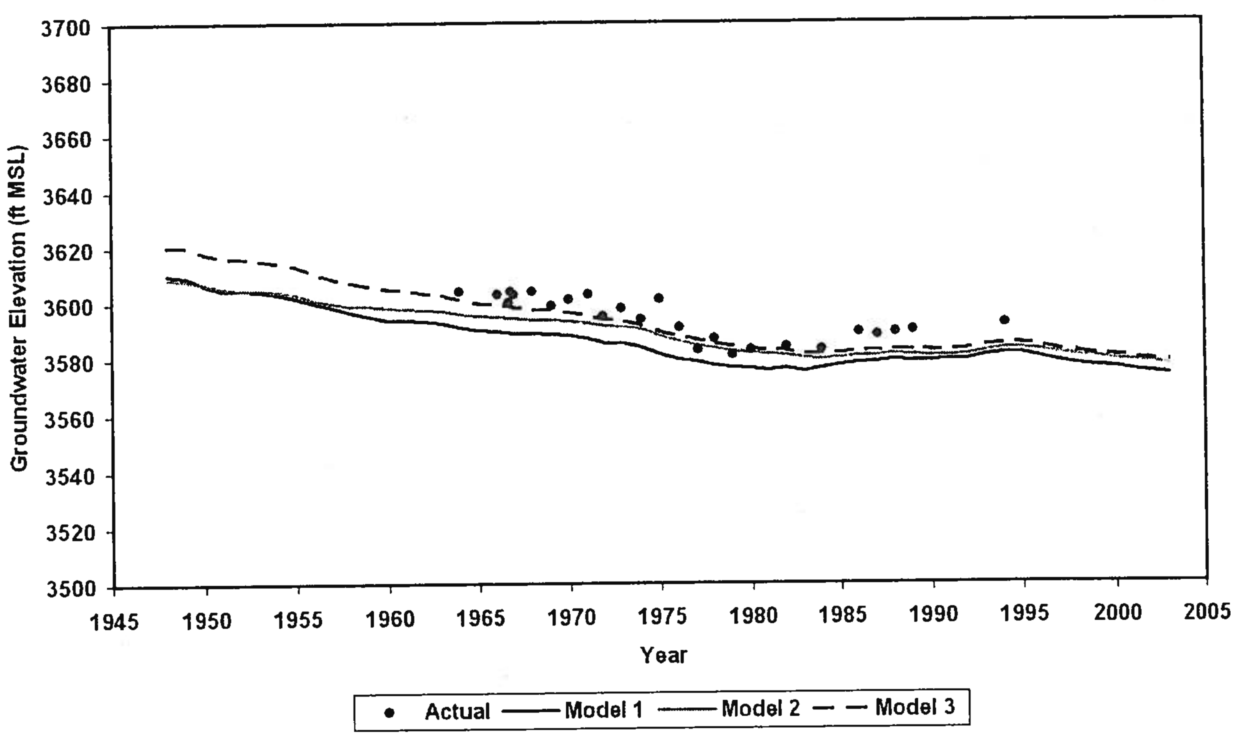
Well 48-15-301
Row 171, Column 100, Pumping Zone 17, Surface Elevation 3640.23 ft



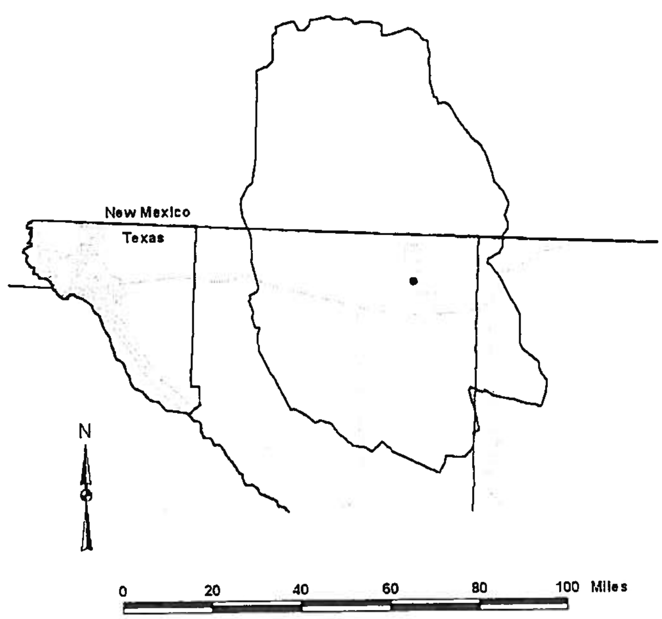
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



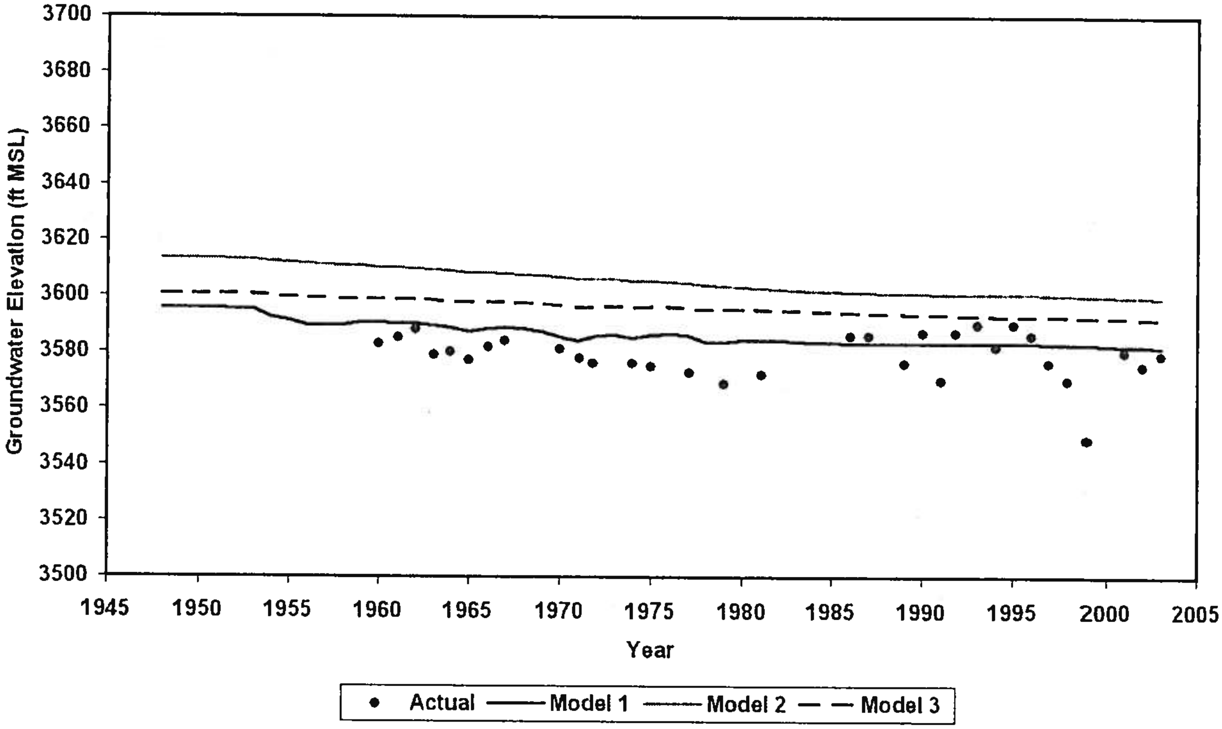
Well 48-15-302
Row 172, Column 105, Pumping Zone 18, Surface Elevation 3626.72 ft



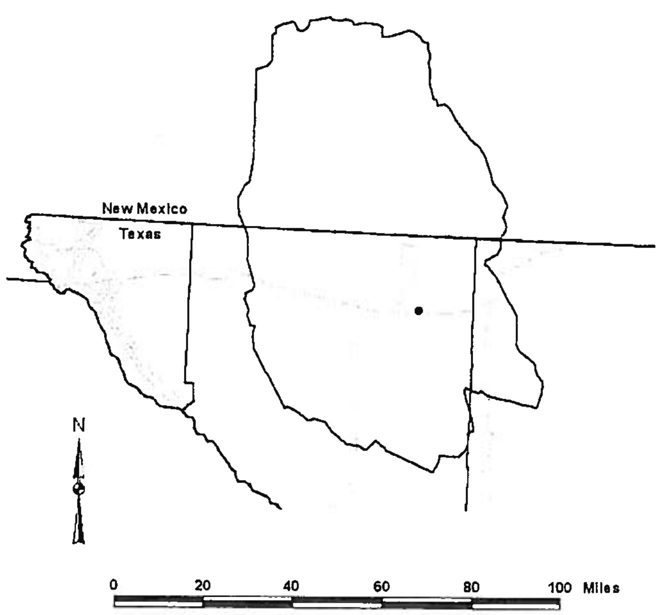
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

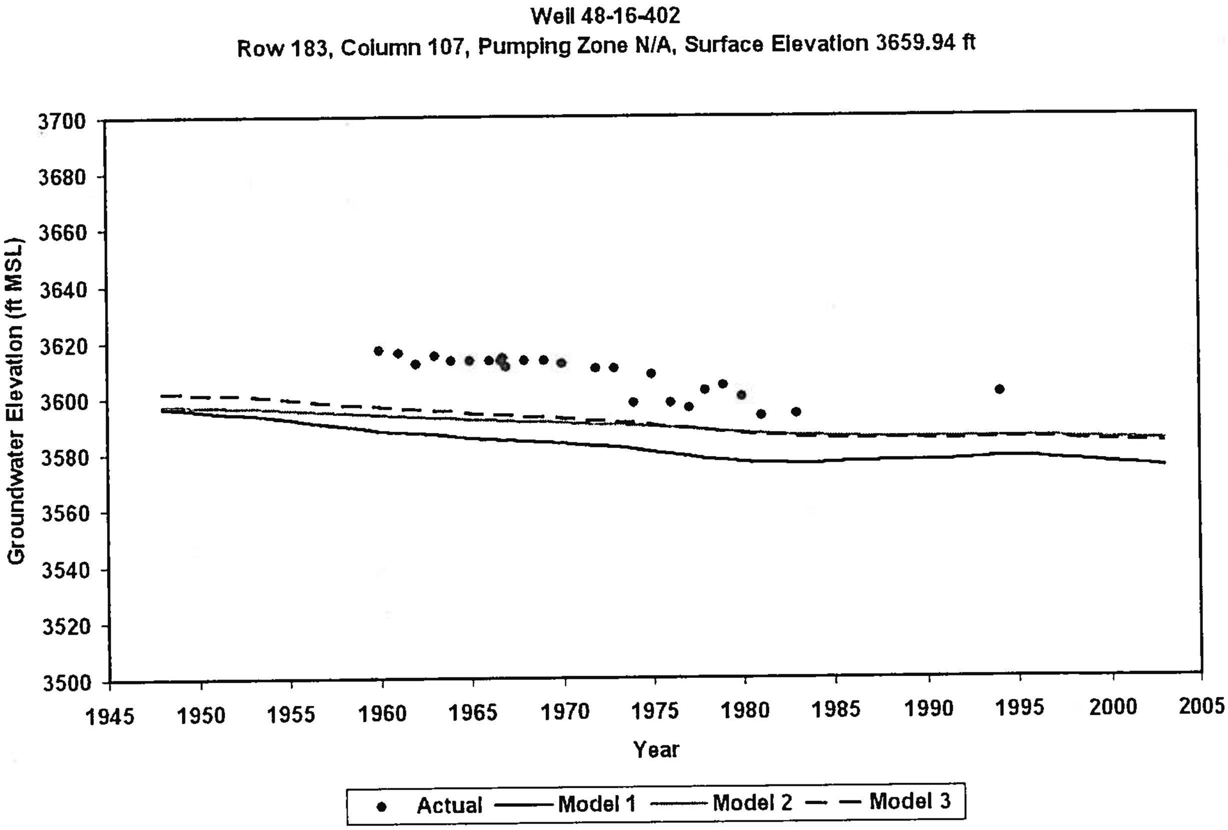


Well 48-15-902
Row 190, Column 98, Pumping Zone 19, Surface Elevation 3751.40 ft

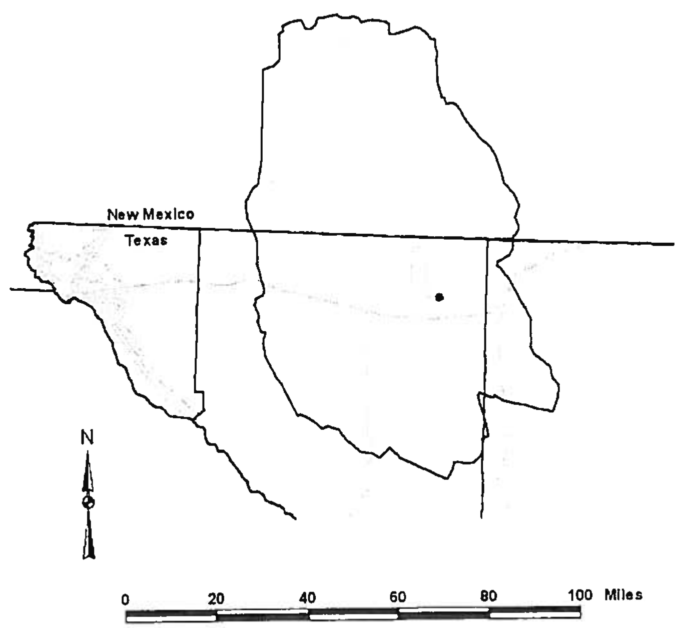


Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2

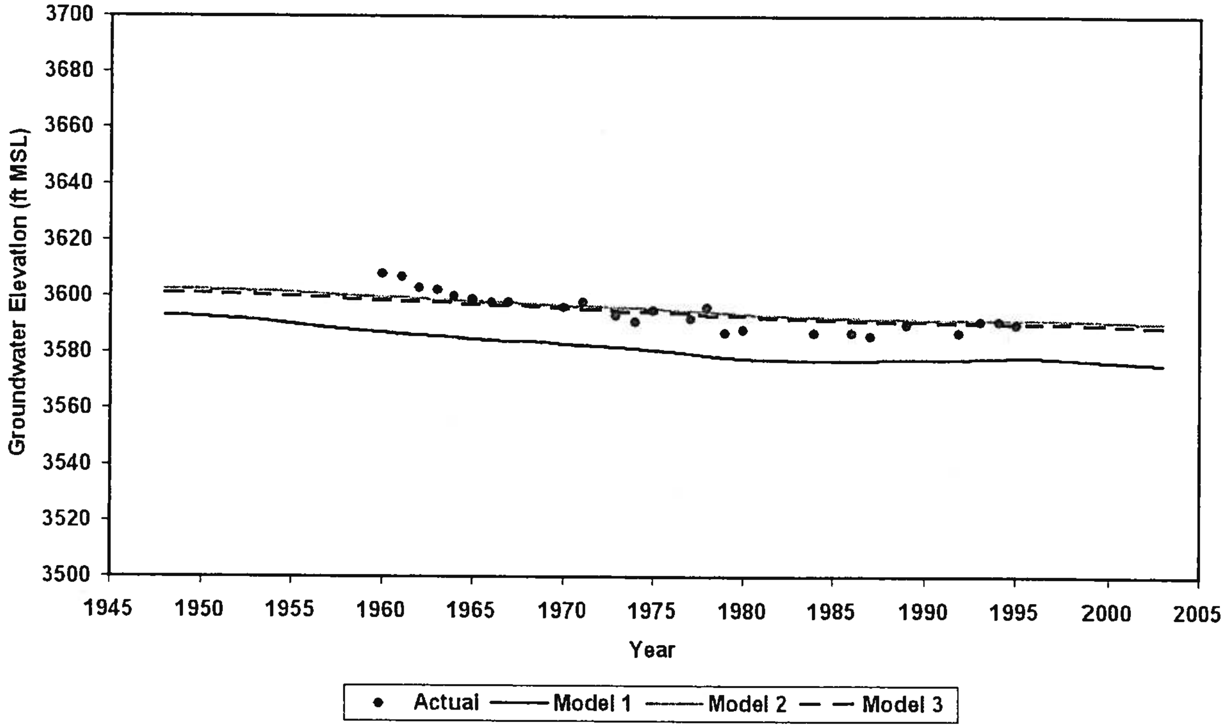




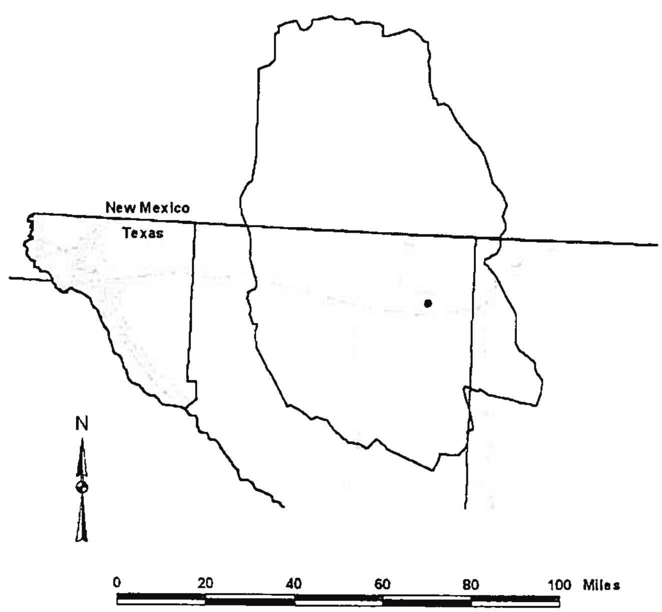
Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



Well 48-16-702
Row 188, Column 105, Pumping Zone N/A, Surface Elevation 3652.06 ft



Note: Model 1 emphasized structural geology concepts (Mayer, 1995)
Model 2 emphasized isotope geochemistry concepts (Eastoe and Hibbs, 2005)
Model 3 was a hybrid of Models 1 and 2



Appendix D

Subregional Groundwater Budgets From Simulations

New HCUWCD Zone 50-Year Simulation Averages All Values in AF/yr

Declining Southern Boundary Assumption

Simulation	Scenario			Inflow					Outflow			Storage Change	Model Error
	Model	Climate	Pumping	Recharge	From New Mexico	From Diablo Plateau	From East	Total	Pumping	ET	Total		
1	M1	C1	P1	448	89,677	6,786	4,390	101,301	95,294	17,735	113,029	-11,725	-3
2	M2	C1	P1	154	63,100	20,435	3,007	86,696	95,462	16,613	112,075	-25,376	-3
3	M3	C1	P1	154	53,813	16,698	4,919	75,584	95,764	11,020	106,784	-31,200	0
4	M1	C2	P1	1,672	96,385	6,948	10,801	115,806	95,294	24,955	120,249	-4,442	-1
5	M2	C2	P1	450	76,803	19,887	4,501	101,641	95,462	18,595	114,057	-12,413	-3
6	M3	C2	P1	450	72,950	14,517	9,379	97,296	95,764	14,583	110,347	-13,051	0
7	M1	C3	P1	486	89,618	6,801	4,741	101,646	95,294	17,819	113,113	-11,466	-1
8	M2	C3	P1	172	63,610	20,526	3,106	87,414	95,462	16,626	112,088	-24,671	-3
9	M3	C3	P1	172	54,463	16,678	5,168	76,481	95,764	10,994	106,758	-30,276	-1
10	M1	C4	P1	1,179	97,029	6,822	8,481	113,511	95,294	24,900	120,194	-6,682	-1
11	M2	C4	P1	354	75,356	19,455	4,211	99,376	95,462	18,790	114,252	-14,873	-3
12	M3	C4	P1	354	69,177	14,373	8,299	92,203	95,764	14,857	110,621	-18,419	1
13	M1	C5	P1	651	90,497	6,819	5,551	103,518	95,294	18,793	114,087	-10,567	-2
14	M2	C5	P1	206	65,362	20,391	3,342	89,301	95,462	16,911	112,373	-23,070	-2
15	M3	C5	P1	206	56,716	16,365	5,772	79,059	95,764	11,434	107,198	-28,140	1
16	M1	C6	P1	694	89,014	6,842	5,510	102,060	95,294	17,435	112,729	-10,669	0
17	M2	C6	P1	208	63,462	20,737	3,049	87,456	95,462	16,463	111,925	-24,465	-4
18	M3	C6	P1	208	55,523	16,875	5,314	77,920	95,764	10,767	106,531	-28,611	0
19	M1	C7	P1	807	93,813	6,785	6,486	107,891	95,294	21,713	117,007	-9,114	-2
20	M2	C7	P1	249	69,690	19,742	3,717	93,398	95,462	17,830	113,292	-19,891	-3
21	M3	C7	P1	249	61,765	15,346	6,746	84,106	95,764	13,066	108,830	-24,724	0
22	M1	C1	P2	448	94,803	7,076	4,950	107,277	109,036	14,044	123,080	-15,801	-2
23	M2	C1	P2	154	66,897	21,808	3,324	92,183	109,229	15,248	124,477	-32,297	3
24	M3	C1	P2	154	56,042	17,889	5,137	79,222	109,581	9,365	118,946	-39,719	-5
25	M1	C2	P2	1,672	100,681	7,227	11,278	120,858	109,036	20,030	129,066	-8,207	-1
26	M2	C2	P2	450	80,489	21,248	4,797	106,984	109,229	16,922	126,151	-19,171	4
27	M3	C2	P2	450	74,658	15,683	9,588	100,379	109,581	12,065	121,646	-21,263	-4
28	M1	C3	P2	486	94,684	7,091	5,300	107,561	109,036	14,062	123,098	-15,534	-3
29	M2	C3	P2	172	67,409	21,900	3,424	92,905	109,229	15,264	124,493	-31,592	4
30	M3	C3	P2	172	56,701	17,873	5,389	80,135	109,581	9,358	118,939	-38,802	-2

Simulation	Scenario			Inflow					Outflow			Storage Change	Model Error
	Model	Climate	Pumping	Recharge	From New Mexico	From Diablo Plateau	From East	Total	Pumping	ET	Total		
31	M1	C4	P2	1,179	101,339	7,099	8,958	118,575	109,036	20,022	129,058	-10,482	-1
32	M2	C4	P2	354	79,001	20,809	4,502	104,666	109,229	17,039	126,268	-21,607	5
33	M3	C4	P2	354	70,940	15,537	8,505	95,336	109,581	12,421	122,002	-26,662	-4
34	M1	C5	P2	651	95,445	7,108	6,098	109,302	109,036	14,856	123,892	-14,589	-1
35	M2	C5	P2	206	69,155	21,763	3,658	94,782	109,229	15,527	124,756	-29,979	5
36	M3	C5	P2	206	58,914	17,555	5,992	82,667	109,581	9,728	119,309	-36,640	-2
37	M1	C6	P2	694	94,167	7,132	6,076	108,069	109,036	13,779	122,815	-14,744	-2
38	M2	C6	P2	208	67,261	22,111	3,368	92,948	109,229	15,107	124,336	-31,392	4
39	M3	C6	P2	208	57,773	18,070	5,535	81,586	109,581	9,153	118,734	-37,146	-2
40	M1	C7	P2	807	98,445	7,068	6,999	113,319	109,036	17,315	126,351	-13,030	-2
41	M2	C7	P2	249	73,436	21,105	4,024	98,814	109,229	16,321	125,550	-26,741	5
42	M3	C7	P2	249	63,781	16,523	6,960	87,513	109,581	11,063	120,644	-33,127	-4
43	M1	C1	P3	448	100,249	7,374	5,574	113,645	122,777	10,936	133,713	-20,066	-2
44	M2	C1	P3	154	70,729	23,190	3,654	97,727	123,004	14,014	137,018	-39,296	5
45	M3	C1	P3	154	58,338	19,094	5,375	82,961	123,389	7,975	131,364	-48,405	2
46	M1	C2	P3	1,672	105,260	7,517	11,836	126,285	122,777	15,783	138,560	-12,274	-1
47	M2	C2	P3	450	84,304	22,623	5,118	112,495	123,004	15,584	138,588	-26,095	2
48	M3	C2	P3	450	76,632	16,876	9,823	103,781	123,389	10,201	133,590	-29,813	4
49	M1	C3	P3	486	100,126	7,390	5,923	113,925	122,777	10,948	133,725	-19,797	-3
50	M2	C3	P3	172	71,240	23,280	3,753	98,445	123,004	14,025	137,029	-38,587	3
51	M3	C3	P3	172	58,998	19,078	5,626	83,874	123,389	7,959	131,348	-47,478	4
52	M1	C4	P3	1,179	106,051	7,388	9,508	124,126	122,777	15,905	138,682	-14,556	0
53	M2	C4	P3	354	82,810	22,183	4,822	110,169	123,004	15,687	138,691	-28,525	3
54	M3	C4	P3	354	72,912	16,722	8,734	98,722	123,389	10,496	133,885	-35,166	3
55	M1	C5	P3	651	100,812	7,406	6,709	115,578	122,777	11,626	134,403	-18,823	-2
56	M2	C5	P3	206	72,982	23,144	3,985	100,317	123,004	14,270	137,274	-36,961	4
57	M3	C5	P3	206	61,186	18,758	6,227	86,377	123,389	8,273	131,662	-45,289	4
58	M1	C6	P3	694	99,656	7,432	6,702	114,484	122,777	10,705	133,482	-18,996	-2
59	M2	C6	P3	208	71,095	23,492	3,698	98,493	123,004	13,882	136,886	-38,396	3
60	M3	C6	P3	208	60,081	19,275	5,774	85,338	123,389	7,787	131,176	-45,842	4

Simulation	Scenario			Inflow					Outflow			Storage Change	Model Error
	Model	Climate	Pumping	Recharge	From New Mexico	From Diablo Plateau	From East	Total	Pumping	ET	Total		
61	M1	C7	P3	807	103,525	7,362	7,581	119,275	122,777	13,702	136,479	-17,202	-2
62	M2	C7	P3	249	77,251	22,482	4,347	104,329	123,004	15,010	138,014	-33,688	3
63	M3	C7	P3	249	65,937	17,719	7,192	91,097	123,389	9,409	132,798	-41,706	5
64	M1	C1	P4	448	88,572	6,763	4,320	100,103	92,215	18,208	110,423	-10,322	2
65	M2	C1	P4	154	62,139	20,284	2,976	85,553	91,808	16,782	108,590	-23,037	0
66	M3	C1	P4	154	52,684	16,403	4,861	74,102	88,740	11,463	100,203	-26,102	1
67	M1	C2	P4	1,672	96,303	6,942	10,792	115,709	95,018	25,062	120,080	-4,372	1
68	M2	C2	P4	450	76,735	19,861	4,495	101,541	95,185	18,639	113,824	-12,284	1
69	M3	C2	P4	450	72,893	14,492	9,375	97,210	95,307	14,654	109,961	-12,754	3
70	M1	C3	P4	486	88,592	6,777	4,672	100,527	92,412	18,310	110,722	-10,198	3
71	M2	C3	P4	172	62,699	20,372	3,074	86,317	92,006	16,798	108,804	-22,487	0
72	M3	C3	P4	172	53,382	16,380	5,110	75,044	89,048	11,438	100,486	-25,442	0
73	M1	C4	P4	1,179	96,946	6,816	8,472	113,413	95,018	25,004	120,022	-6,610	1
74	M2	C4	P4	354	75,287	19,428	4,206	99,275	95,185	18,833	114,018	-14,744	1
75	M3	C4	P4	354	69,015	14,347	8,296	92,012	94,647	14,931	109,578	-17,568	2
76	M1	C5	P4	651	89,685	6,801	5,497	102,634	92,969	19,193	112,162	-9,528	0
77	M2	C5	P4	206	64,625	20,276	3,318	88,425	92,664	17,046	109,710	-21,286	1
78	M3	C5	P4	206	55,810	16,133	5,728	77,877	90,086	11,795	101,881	-24,006	2
79	M1	C6	P4	694	87,799	6,812	5,424	100,729	91,936	18,038	109,974	-9,248	3
80	M2	C6	P4	208	62,399	20,544	3,007	86,158	91,538	16,671	108,209	-22,051	0
81	M3	C6	P4	208	54,356	16,522	5,243	76,329	88,542	11,279	99,821	-23,494	2
82	M1	C7	P4	807	93,589	6,780	6,475	107,651	94,560	21,840	116,400	-8,752	3
83	M2	C7	P4	249	69,413	19,706	3,713	93,081	94,258	17,882	112,140	-19,060	1
84	M3	C7	P4	249	61,236	15,260	6,733	83,478	92,372	13,239	105,611	-22,133	0
85	M1	C1	P5	448	91,147	6,954	4,633	103,182	99,708	15,583	115,291	-12,111	2
86	M2	C1	P5	154	63,986	21,119	3,163	88,422	98,563	15,921	114,484	-26,061	-1
87	M3	C1	P5	154	55,314	17,874	5,119	78,461	105,161	9,343	114,504	-36,044	1
88	M1	C2	P5	1,672	99,418	7,178	11,165	119,433	105,268	20,960	126,228	-6,799	4
89	M2	C2	P5	450	79,361	20,998	4,742	105,551	105,072	17,191	122,263	-16,714	2
90	M3	C2	P5	450	73,833	15,441	9,538	99,262	103,890	12,537	116,427	-17,165	0

Simulation	Scenario			Inflow					Outflow			Storage Change	Model Error
	Model	Climate	Pumping	Recharge	From New Mexico	From Diablo Plateau	From East	Total	Pumping	ET	Total		
91	M1	C3	P5	486	91,047	6,963	4,979	103,475	99,708	15,703	115,411	-11,937	1
92	M2	C3	P5	172	64,547	21,189	3,258	89,166	98,751	15,954	114,705	-25,540	1
93	M3	C3	P5	172	54,424	17,085	5,232	76,913	95,614	10,394	106,008	-29,098	3
94	M1	C4	P5	1,179	100,227	7,064	8,871	117,341	105,744	20,706	126,450	-9,113	4
95	M2	C4	P5	354	77,945	20,637	4,466	103,402	105,198	17,235	122,433	-19,034	3
96	M3	C4	P5	354	70,010	15,326	8,464	94,154	103,437	12,813	116,250	-22,098	2
97	M1	C5	P5	651	92,186	6,994	5,813	105,644	100,569	16,403	116,972	-11,332	4
98	M2	C5	P5	206	66,524	21,134	3,510	91,374	99,597	16,146	115,743	-24,371	2
99	M3	C5	P5	206	56,842	16,849	5,851	79,748	96,789	10,679	107,468	-27,723	3
100	M1	C6	P5	694	90,333	6,999	5,735	103,761	99,322	15,442	114,764	-11,006	3
101	M2	C6	P5	208	64,245	21,368	3,192	89,013	98,275	15,826	114,101	-25,089	1
102	M3	C6	P5	208	55,414	17,228	5,364	78,214	95,154	10,248	105,402	-27,190	2
103	M1	C7	P5	807	96,319	7,001	6,826	110,953	103,203	18,405	121,608	-10,656	1
104	M2	C7	P5	249	71,567	20,719	3,937	96,472	102,254	16,719	118,973	-22,503	2
105	M3	C7	P5	249	62,221	16,084	6,872	85,426	99,734	11,722	111,456	-26,030	0
106	M1	C1	P6	448	93,710	7,115	4,930	106,203	106,664	13,623	120,287	-14,083	-1
107	M2	C1	P6	154	65,908	21,857	3,332	91,251	105,614	15,208	120,822	-29,573	2
108	M3	C1	P6	154	55,314	17,874	5,119	78,461	105,161	9,343	114,504	-36,044	1
109	M1	C2	P6	1,672	101,500	7,332	11,430	121,934	111,894	18,547	130,441	-8,507	0
110	M2	C2	P6	450	81,061	21,708	4,903	108,122	111,234	16,468	127,702	-19,581	1
111	M3	C2	P6	450	74,680	16,138	9,667	100,935	110,573	11,280	121,853	-20,919	1
112	M1	C3	P6	486	93,558	7,127	5,275	106,446	106,575	13,696	120,271	-13,823	-2
113	M2	C3	P6	172	66,366	21,918	3,424	91,880	105,424	15,251	120,675	-28,796	1
114	M3	C3	P6	172	55,931	17,822	5,363	79,288	104,872	9,391	114,263	-34,977	2
115	M1	C4	P6	1,179	102,320	7,222	9,137	119,858	112,379	18,289	130,668	-10,809	-1
116	M2	C4	P6	354	79,670	21,364	4,632	106,020	111,450	16,488	127,938	-21,920	2
117	M3	C4	P6	354	70,924	16,073	8,598	95,949	110,528	11,460	121,988	-26,039	0
118	M1	C5	P6	651	94,506	7,154	6,096	108,407	107,051	14,368	121,419	-13,013	1
119	M2	C5	P6	206	68,276	21,847	3,673	94,002	105,992	15,455	121,447	-27,445	0
120	M3	C5	P6	206	58,216	17,563	5,978	81,963	105,342	9,682	115,024	-33,063	2

Simulation	Scenario			Inflow					Outflow			Storage Change	Model Error
	Model	Climate	Pumping	Recharge	From New Mexico	From Diablo Plateau	From East	Total	Pumping	ET	Total		
121	M1	C6	P6	694	92,887	7,161	6,032	106,774	106,188	13,499	119,687	-12,912	-1
122	M2	C6	P6	208	66,160	22,113	3,363	91,844	105,227	15,108	120,335	-28,492	1
123	M3	C6	P6	208	56,970	17,996	5,504	80,678	104,682	9,208	113,890	-33,213	1
124	M1	C7	P6	807	98,584	7,162	7,106	113,659	109,917	16,150	126,067	-12,408	0
125	M2	C7	P6	249	73,331	21,466	4,107	99,153	108,676	15,975	124,651	-25,497	-1
126	M3	C7	P6	249	63,420	16,807	7,001	87,477	107,754	10,589	118,343	-30,868	2
127	M1	C1	P7	448	88,991	6,774	4,351	100,564	93,347	17,998	111,345	-10,783	2
128	M2	C1	P7	154	62,472	20,346	2,990	85,962	93,033	16,715	109,748	-23,785	-1
129	M3	C1	P7	154	52,916	16,501	4,882	74,453	90,176	11,328	101,504	-27,053	2
130	M1	C2	P7	1,672	96,303	6,942	10,792	115,709	95,018	25,062	120,080	-4,372	1
131	M2	C2	P7	450	76,735	19,861	4,495	101,541	95,185	18,639	113,824	-12,284	1
132	M3	C2	P7	450	72,920	14,494	9,374	97,238	95,487	14,642	110,129	-12,894	3
133	M1	C3	P7	486	89,011	6,789	4,706	100,992	93,535	18,070	111,605	-10,616	3
134	M2	C3	P7	172	63,065	20,452	3,093	86,782	93,321	16,712	110,033	-23,252	1
135	M3	C3	P7	172	53,657	16,493	5,133	75,455	90,746	11,281	102,027	-26,573	1
136	M1	C4	P7	1,179	96,946	6,816	8,472	113,413	95,018	25,004	120,022	-6,610	1
137	M2	C4	P7	354	75,287	19,428	4,206	99,275	95,185	18,833	114,018	-14,744	1
138	M3	C4	P7	354	69,102	14,350	8,295	92,101	95,207	14,915	110,122	-18,023	2
139	M1	C5	P7	651	90,057	6,810	5,526	103,044	93,994	18,993	112,987	-9,943	0
140	M2	C5	P7	206	64,929	20,330	3,330	88,795	93,781	16,983	110,764	-21,969	0
141	M3	C5	P7	206	56,039	16,218	5,744	78,207	91,513	11,671	103,184	-24,978	1
142	M1	C6	P7	694	88,231	6,826	5,462	101,213	93,068	17,780	110,848	-9,637	2
143	M2	C6	P7	208	62,740	20,625	3,027	86,600	92,763	16,586	109,349	-22,750	1
144	M3	C6	P7	208	54,637	16,642	5,268	76,755	90,267	11,118	101,385	-24,633	3
145	M1	C7	P7	807	93,706	6,780	6,478	107,771	94,928	21,810	116,738	-8,971	4
146	M2	C7	P7	249	69,563	19,714	3,712	93,238	94,915	17,868	112,783	-19,544	-1
147	M3	C7	P7	249	61,397	15,297	6,740	83,683	93,419	13,169	106,588	-22,905	0
148	M1	C1	P8	448	89,335	6,779	4,372	100,934	94,272	17,862	112,134	-11,201	1
149	M2	C1	P8	154	62,737	20,390	3,000	86,281	93,970	16,667	110,637	-24,356	0
150	M3	C1	P8	154	53,147	16,571	4,896	74,768	91,604	11,227	102,831	-28,064	1

Simulation	Scenario			Inflow					Outflow			Storage Change	Model Error
	Model	Climate	Pumping	Recharge	From New Mexico	From Diablo Plateau	From East	Total	Pumping	ET	Total		
151	M1	C2	P8	1,672	96,303	6,942	10,792	115,709	95,018	25,062	120,080	-4,372	1
152	M2	C2	P8	450	76,735	19,861	4,495	101,541	95,185	18,639	113,824	-12,284	1
153	M3	C2	P8	450	72,920	14,494	9,374	97,238	95,487	14,642	110,129	-12,894	3
154	M1	C3	P8	486	89,315	6,794	4,725	101,320	94,371	17,946	112,317	-10,999	2
155	M2	C3	P8	172	63,314	20,487	3,101	87,074	94,249	16,672	110,921	-23,846	-1
156	M3	C3	P8	172	53,875	16,572	5,149	75,768	92,082	11,169	103,251	-27,484	1
157	M1	C4	P8	1,179	96,946	6,816	8,472	113,413	95,018	25,004	120,022	-6,610	1
158	M2	C4	P8	354	75,287	19,428	4,206	99,275	95,185	18,833	114,018	-14,744	1
159	M3	C4	P8	354	69,144	14,350	8,295	92,143	95,487	14,913	110,400	-18,260	3
160	M1	C5	P8	651	90,323	6,813	5,539	103,326	94,748	18,898	113,646	-10,320	0
161	M2	C5	P8	206	65,167	20,359	3,336	89,068	94,636	16,948	111,584	-22,516	0
162	M3	C5	P8	206	56,269	16,287	5,759	78,521	92,950	11,568	104,518	-25,997	0
163	M1	C6	P8	694	88,568	6,832	5,485	101,579	93,994	17,625	111,619	-10,040	0
164	M2	C6	P8	208	63,028	20,676	3,038	86,950	93,781	16,532	110,313	-23,362	-1
165	M3	C6	P8	208	54,858	16,723	5,284	77,073	91,622	11,006	102,628	-25,556	1
166	M1	C7	P8	807	93,726	6,780	6,477	107,790	95,018	21,808	116,826	-9,039	3
167	M2	C7	P8	249	69,618	19,716	3,712	93,295	95,185	17,865	113,050	-19,756	1
168	M3	C7	P8	249	61,548	15,317	6,743	83,857	94,368	13,130	107,498	-23,642	1
169	M1	C1	P9	448	89,335	6,779	4,372	100,934	94,272	17,862	112,134	-11,201	1
170	M2	C1	P9	154	62,737	20,390	3,000	86,281	93,970	16,667	110,637	-24,356	0
171	M3	C1	P9	154	53,147	16,571	4,896	74,768	91,604	11,227	102,831	-28,064	1
172	M1	C2	P9	1,672	96,303	6,942	10,792	115,709	95,018	25,062	120,080	-4,372	1
173	M2	C2	P9	450	76,735	19,861	4,495	101,541	95,185	18,639	113,824	-12,284	1
174	M3	C2	P9	450	72,920	14,494	9,374	97,238	95,487	14,642	110,129	-12,894	3
175	M1	C3	P9	486	89,315	6,794	4,725	101,320	94,371	17,946	112,317	-10,999	2
176	M2	C3	P9	172	63,314	20,487	3,101	87,074	94,249	16,672	110,921	-23,846	-1
177	M3	C3	P9	172	53,875	16,572	5,149	75,768	92,082	11,169	103,251	-27,484	1
178	M1	C4	P9	1,179	96,946	6,816	8,472	113,413	95,018	25,004	120,022	-6,610	1
179	M2	C4	P9	354	75,287	19,428	4,206	99,275	95,185	18,833	114,018	-14,744	1
180	M3	C4	P9	354	69,144	14,350	8,295	92,143	95,487	14,913	110,400	-18,260	3

Simulation	Scenario			Inflow					Outflow			Storage Change	Model Error
	Model	Climate	Pumping	Recharge	From New Mexico	From Diablo Plateau	From East	Total	Pumping	ET	Total		
181	M1	C5	P9	651	90,323	6,813	5,539	103,326	94,748	18,898	113,646	-10,320	0
182	M2	C5	P9	206	65,167	20,359	3,336	89,068	94,636	16,948	111,584	-22,516	0
183	M3	C5	P9	206	56,269	16,287	5,759	78,521	92,950	11,568	104,518	-25,997	0
184	M1	C6	P9	694	88,568	6,832	5,485	101,579	93,994	17,625	111,619	-10,040	0
185	M2	C6	P9	208	63,028	20,676	3,038	86,950	93,781	16,532	110,313	-23,362	-1
186	M3	C6	P9	208	54,858	16,723	5,284	77,073	91,622	11,006	102,628	-25,556	1
187	M1	C7	P9	807	93,726	6,780	6,477	107,790	95,018	21,808	116,826	-9,039	3
188	M2	C7	P9	249	69,618	19,716	3,712	93,295	95,185	17,865	113,050	-19,756	1
189	M3	C7	P9	249	61,548	15,317	6,743	83,857	94,368	13,130	107,498	-23,642	1
190	M1	C1	P10	448	89,335	6,779	4,372	100,934	94,272	17,862	112,134	-11,201	1
191	M2	C1	P10	154	62,737	20,390	3,000	86,281	93,970	16,667	110,637	-24,356	0
192	M3	C1	P10	154	53,147	16,571	4,896	74,768	91,604	11,227	102,831	-28,064	1
193	M1	C2	P10	1,672	96,303	6,942	10,792	115,709	95,018	25,062	120,080	-4,372	1
194	M2	C2	P10	450	76,735	19,861	4,495	101,541	95,185	18,639	113,824	-12,284	1
195	M3	C2	P10	450	72,920	14,494	9,374	97,238	95,487	14,642	110,129	-12,894	3
196	M1	C3	P10	486	89,315	6,794	4,725	101,320	94,371	17,946	112,317	-10,999	2
197	M2	C3	P10	172	63,314	20,487	3,101	87,074	94,249	16,672	110,921	-23,846	-1
198	M3	C3	P10	172	53,875	16,572	5,149	75,768	92,082	11,169	103,251	-27,484	1
199	M1	C4	P10	1,179	96,946	6,816	8,472	113,413	95,018	25,004	120,022	-6,610	1
200	M2	C4	P10	354	75,287	19,428	4,206	99,275	95,185	18,833	114,018	-14,744	1
201	M3	C4	P10	354	69,144	14,350	8,295	92,143	95,487	14,913	110,400	-18,260	3
202	M1	C5	P10	651	90,323	6,813	5,539	103,326	94,748	18,898	113,646	-10,320	0
203	M2	C5	P10	206	65,167	20,359	3,336	89,068	94,636	16,948	111,584	-22,516	0
204	M3	C5	P10	206	56,269	16,287	5,759	78,521	92,950	11,568	104,518	-25,997	0
205	M1	C6	P10	694	88,568	6,832	5,485	101,579	93,994	17,625	111,619	-10,040	0
206	M2	C6	P10	208	63,028	20,676	3,038	86,950	93,781	16,532	110,313	-23,362	-1
207	M3	C6	P10	208	54,858	16,723	5,284	77,073	91,622	11,006	102,628	-25,556	1
208	M1	C7	P10	807	93,726	6,780	6,477	107,790	95,018	21,808	116,826	-9,039	3
209	M2	C7	P10	249	69,618	19,716	3,712	93,295	95,185	17,865	113,050	-19,756	1
210	M3	C7	P10	249	61,548	15,317	6,743	83,857	94,368	13,130	107,498	-23,642	1

Simulation	Scenario			Inflow					Outflow			Storage Change	Model Error
	Model	Climate	Pumping	Recharge	From New Mexico	From Diablo Plateau	From East	Total	Pumping	ET	Total		
211	M1	C1	Zero	448	63,657	4,850	4,910	73,865	0	61,151	61,151	12,714	0
212	M2	C1	Zero	154	43,707	11,250	3,355	58,466	0	42,088	42,088	16,377	1
213	M3	C1	Zero	154	44,785	9,144	6,028	60,111	0	41,587	41,587	18,524	0
214	M1	C2	Zero	1,672	70,872	5,027	11,298	88,869	0	69,077	69,077	19,791	1
215	M2	C2	Zero	450	58,761	10,776	4,925	74,912	0	46,457	46,457	28,452	3
216	M3	C2	Zero	450	65,184	7,078	10,548	83,260	0	47,894	47,894	35,364	2
217	M1	C3	Zero	486	63,681	4,866	5,259	74,292	0	61,322	61,322	12,969	1
218	M2	C3	Zero	172	44,220	11,336	3,453	59,181	0	42,143	42,143	17,038	0
219	M3	C3	Zero	172	45,520	9,119	6,274	61,085	0	41,678	41,678	19,406	1
220	M1	C4	Zero	1,179	71,538	4,902	8,984	86,603	0	69,102	69,102	17,498	3
221	M2	C4	Zero	354	57,433	10,356	4,643	72,786	0	46,779	46,779	26,005	2
222	M3	C4	Zero	354	61,434	6,958	9,470	78,216	0	48,221	48,221	29,994	1
223	M1	C5	Zero	651	64,739	4,887	6,076	76,353	0	62,520	62,520	13,832	1
224	M2	C5	Zero	206	46,194	11,217	3,705	61,322	0	42,836	42,836	18,483	3
225	M3	C5	Zero	206	48,046	8,830	6,885	63,967	0	42,630	42,630	21,335	2
226	M1	C6	Zero	694	63,034	4,904	6,017	74,649	0	60,838	60,838	13,809	2
227	M2	C6	Zero	208	43,913	11,539	3,386	59,046	0	41,690	41,690	17,354	2
228	M3	C6	Zero	208	46,369	9,302	6,418	62,297	0	41,113	41,113	21,181	3
229	M1	C7	Zero	807	68,267	4,862	7,024	80,960	0	65,811	65,811	15,147	2
230	M2	C7	Zero	249	51,220	10,617	4,126	66,212	0	44,930	44,930	21,280	2
231	M3	C7	Zero	249	53,690	7,890	7,887	69,716	0	45,511	45,511	24,204	1
232	M1	C1	P11	448	69,271	5,460	2,385	77,564	26,508	45,872	72,380	5,184	0
233	M2	C1	P11	154	47,295	13,933	1,900	63,282	26,512	31,927	58,439	4,841	2
234	M3	C1	P11	154	45,593	11,228	4,151	61,126	26,613	29,488	56,101	5,023	2
235	M1	C2	P11	1,672	76,766	5,643	8,925	93,006	26,508	54,582	81,090	11,914	2
236	M2	C2	P11	450	62,421	13,456	3,481	79,808	26,512	36,713	63,225	16,581	2
237	M3	C2	P11	450	66,170	9,203	8,689	84,512	26,613	36,961	63,574	20,934	4
238	M1	C3	P11	486	69,305	5,476	2,740	78,007	26,508	46,082	72,590	5,417	0
239	M2	C3	P11	172	47,820	14,019	1,999	64,010	26,512	32,003	58,515	5,493	2
240	M3	C3	P11	172	46,335	11,203	4,397	62,107	26,613	29,650	56,263	5,842	2

Simulation	Scenario			Inflow					Outflow			Storage Change	Model Error
	Model	Climate	Pumping	Recharge	From New Mexico	From Diablo Plateau	From East	Total	Pumping	ET	Total		
241	M1	C4	P11	1,179	77,418	5,517	6,601	90,715	26,508	54,521	81,029	9,685	1
242	M2	C4	P11	354	61,074	13,035	3,197	77,660	26,512	36,989	63,501	14,158	1
243	M3	C4	P11	354	62,404	9,088	7,614	79,460	26,613	37,215	63,828	15,630	2
244	M1	C5	P11	651	70,408	5,498	3,574	80,131	26,508	47,406	73,914	6,216	1
245	M2	C5	P11	206	49,761	13,900	2,250	66,117	26,512	32,690	59,202	6,913	2
246	M3	C5	P11	206	48,873	10,917	5,007	65,003	26,613	30,718	57,331	7,670	2
247	M1	C6	P11	694	68,640	5,513	3,490	78,337	26,508	45,570	72,078	6,258	1
248	M2	C6	P11	208	47,544	14,224	1,932	63,908	26,512	31,569	58,081	5,824	3
249	M3	C6	P11	208	47,186	11,384	4,542	63,320	26,613	29,056	55,669	7,648	3
250	M1	C7	P11	807	74,050	5,476	4,573	84,906	26,508	50,973	77,481	7,424	1
251	M2	C7	P11	249	54,771	13,294	2,673	70,987	26,512	34,867	61,379	9,607	1
252	M3	C7	P11	249	54,549	9,992	6,017	70,807	26,613	33,932	60,545	10,260	2
253	M1	C1	P12	448	73,072	5,713	2,729	81,962	40,210	39,653	79,863	2,096	3
254	M2	C1	P12	154	50,058	15,184	2,078	67,474	40,247	27,903	68,150	-676	0
255	M3	C1	P12	154	46,897	12,247	4,274	63,572	40,388	24,455	64,843	-1,273	2
256	M1	C2	P12	1,672	80,685	5,895	9,287	97,539	40,210	48,648	88,858	8,681	0
257	M2	C2	P12	450	64,962	14,696	3,650	83,758	40,247	32,325	72,572	11,185	1
258	M3	C2	P12	450	67,445	10,209	8,805	86,909	40,388	31,854	72,242	14,663	4
259	M1	C3	P12	486	73,111	5,728	3,082	82,407	40,210	39,869	80,079	2,328	0
260	M2	C3	P12	172	50,578	15,271	2,177	68,198	40,247	27,966	68,213	-16	1
261	M3	C3	P12	172	47,634	12,223	4,519	64,548	40,388	24,593	64,981	-436	3
262	M1	C4	P12	1,179	81,326	5,771	6,961	95,237	40,210	48,535	88,745	6,489	3
263	M2	C4	P12	354	63,594	14,272	3,367	81,587	40,247	32,576	72,823	8,763	1
264	M3	C4	P12	354	63,663	10,090	7,729	81,836	40,388	32,024	72,412	9,422	2
265	M1	C5	P12	651	74,223	5,751	3,916	84,541	40,210	41,200	81,410	3,130	1
266	M2	C5	P12	206	52,478	15,149	2,427	70,260	40,247	28,590	68,837	1,423	0
267	M3	C5	P12	206	50,144	11,932	5,125	67,407	40,388	25,583	65,971	1,434	2
268	M1	C6	P12	694	72,441	5,765	3,832	82,732	40,210	39,360	79,570	3,162	0
269	M2	C6	P12	208	50,329	15,477	2,111	68,125	40,247	27,571	67,818	305	2
270	M3	C6	P12	208	48,504	12,407	4,666	65,785	40,388	24,049	64,437	1,346	2

Simulation	Scenario			Inflow					Outflow			Storage Change	Model Error
	Model	Climate	Pumping	Recharge	From New Mexico	From Diablo Plateau	From East	Total	Pumping	ET	Total		
271	M1	C7	P12	807	77,864	5,727	4,917	89,315	40,210	44,769	84,979	4,335	1
272	M2	C7	P12	249	57,333	14,537	2,846	74,965	40,247	30,553	70,800	4,163	2
273	M3	C7	P12	249	55,795	10,995	6,132	73,171	40,388	28,699	69,087	4,083	1
274	M1	C1	P13	448	76,889	5,970	3,084	86,391	53,912	33,540	87,452	-1,062	1
275	M2	C1	P13	154	52,966	16,455	2,267	71,842	53,981	24,203	78,184	-6,344	2
276	M3	C1	P13	154	48,287	13,298	4,411	66,150	54,164	19,945	74,109	-7,959	0
277	M1	C2	P13	1,672	84,527	6,151	9,644	101,994	53,912	42,548	96,460	5,532	2
278	M2	C2	P13	450	67,598	15,956	3,837	87,841	53,981	28,249	82,230	5,610	1
279	M3	C2	P13	450	68,709	11,231	8,923	89,313	54,164	26,781	80,945	8,368	0
280	M1	C3	P13	486	76,921	5,984	3,436	86,827	53,912	33,738	87,650	-823	0
281	M2	C3	P13	172	53,481	16,542	2,367	72,562	53,981	24,259	78,240	-5,679	1
282	M3	C3	P13	172	49,016	13,276	4,655	67,119	54,164	20,055	74,219	-7,101	1
283	M1	C4	P13	1,179	85,166	6,025	7,316	99,686	53,912	42,427	96,339	3,345	2
284	M2	C4	P13	354	66,205	15,532	3,552	85,643	53,981	28,484	82,465	3,176	2
285	M3	C4	P13	354	64,922	11,108	7,848	84,232	54,164	26,953	81,117	3,113	2
286	M1	C5	P13	651	78,022	6,007	4,268	88,948	53,912	35,041	88,953	-8	3
287	M2	C5	P13	206	55,350	16,418	2,616	74,590	53,981	24,835	78,816	-4,228	2
288	M3	C5	P13	206	51,505	12,979	5,260	69,950	54,164	20,954	75,118	-5,169	1
289	M1	C6	P13	694	76,260	6,022	4,187	87,163	53,912	33,243	87,155	8	0
290	M2	C6	P13	208	53,255	16,749	2,300	72,512	53,981	23,895	77,876	-5,367	3
291	M3	C6	P13	208	49,900	13,463	4,805	68,376	54,164	19,558	73,722	-5,347	1
292	M1	C7	P13	807	81,699	5,984	5,273	93,763	53,912	38,660	92,572	1,188	3
293	M2	C7	P13	249	60,086	15,800	3,034	79,169	53,981	26,652	80,633	-1,465	1
294	M3	C7	P13	249	57,088	12,025	6,253	75,615	54,164	23,815	77,979	-2,366	2
295	M1	C1	P14	448	80,858	6,233	3,472	91,011	67,614	27,773	95,387	-4,377	1
296	M2	C1	P14	154	56,051	17,741	2,467	76,413	67,716	20,881	88,597	-12,184	0
297	M3	C1	P14	154	49,838	14,381	4,554	68,927	67,939	16,006	83,945	-15,018	0
298	M1	C2	P14	1,672	88,393	6,411	10,011	106,487	67,614	36,567	104,181	2,305	1
299	M2	C2	P14	450	70,409	17,236	4,038	92,133	67,716	24,552	92,268	-138	3
300	M3	C2	P14	450	70,006	12,283	9,051	91,790	67,939	22,077	90,016	1,774	0

Simulation	Scenario			Inflow					Outflow			Storage Change	Model Error
	Model	Climate	Pumping	Recharge	From New Mexico	From Diablo Plateau	From East	Total	Pumping	ET	Total		
301	M1	C3	P14	486	80,884	6,248	3,824	91,442	67,614	27,961	95,575	-4,133	0
302	M2	C3	P14	172	56,563	17,828	2,566	77,129	67,716	20,920	88,636	-11,506	-1
303	M3	C3	P14	172	50,515	14,359	4,804	69,850	67,939	16,055	83,994	-14,145	1
304	M1	C4	P14	1,179	89,016	6,285	7,682	104,162	67,614	36,398	104,012	148	2
305	M2	C4	P14	354	68,991	16,809	3,751	89,905	67,716	24,765	92,481	-2,577	1
306	M3	C4	P14	354	66,224	12,155	7,975	86,708	67,939	22,289	90,228	-3,522	2
307	M1	C5	P14	651	81,951	6,269	4,649	93,520	67,614	29,200	96,814	-3,296	2
308	M2	C5	P14	206	58,405	17,704	2,815	79,130	67,716	21,448	89,164	-10,035	1
309	M3	C5	P14	206	52,951	14,059	5,409	72,625	67,939	16,856	84,795	-12,171	1
310	M1	C6	P14	694	80,238	6,286	4,577	91,795	67,614	27,485	95,099	-3,304	0
311	M2	C6	P14	208	56,357	18,037	2,501	77,103	67,716	20,599	88,315	-11,215	3
312	M3	C6	P14	208	51,464	14,548	4,946	71,166	67,939	15,623	83,562	-12,397	1
313	M1	C7	P14	807	85,550	6,244	5,638	98,239	67,614	32,656	100,270	-2,035	4
314	M2	C7	P14	249	63,022	17,082	3,233	83,586	67,716	23,115	90,831	-7,246	1
315	M3	C7	P14	249	58,469	13,090	6,395	78,203	67,939	19,498	87,437	-9,234	0
316	M1	C1	P15	448	84,995	6,502	3,896	95,841	81,317	22,407	103,724	-7,882	-1
317	M2	C1	P15	154	59,365	19,059	2,709	81,287	81,450	18,324	99,774	-18,488	1
318	M3	C1	P15	154	51,502	15,494	4,716	71,866	80,656	13,105	93,761	-21,895	0
319	M1	C2	P15	1,672	92,278	6,674	10,385	111,009	81,317	30,643	111,960	-953	2
320	M2	C2	P15	450	73,433	18,533	4,249	96,665	81,450	21,236	102,686	-6,024	3
321	M3	C2	P15	450	71,390	13,365	9,198	94,403	81,713	17,928	99,641	-5,240	2
322	M1	C3	P15	486	84,994	6,516	4,246	96,242	81,317	22,549	103,866	-7,623	-1
323	M2	C3	P15	172	59,865	19,148	2,807	81,992	81,450	18,323	99,773	-17,782	1
324	M3	C3	P15	172	52,198	15,482	4,968	72,820	80,936	13,092	94,028	-21,210	2
325	M1	C4	P15	1,179	92,911	6,548	8,060	108,698	81,317	30,523	111,840	-3,143	1
326	M2	C4	P15	354	71,997	18,103	3,961	94,415	81,450	21,432	102,882	-8,468	1
327	M3	C4	P15	354	67,615	13,234	8,121	89,324	81,713	18,200	99,913	-10,590	1
328	M1	C5	P15	651	86,013	6,537	5,063	98,264	81,317	23,684	105,001	-6,736	-1
329	M2	C5	P15	206	61,663	19,018	3,049	83,936	81,450	18,713	100,163	-16,229	2
330	M3	C5	P15	206	54,608	15,179	5,575	75,568	81,415	13,675	95,090	-19,524	2

Simulation	Scenario			Inflow					Outflow			Storage Change	Model Error
	Model	Climate	Pumping	Recharge	From New Mexico	From Diablo Plateau	From East	Total	Pumping	ET	Total		
331	M1	C6	P15	694	84,368	6,556	5,005	96,623	81,317	22,110	103,427	-6,805	1
332	M2	C6	P15	208	59,700	19,358	2,747	82,013	81,450	18,111	99,561	-17,550	2
333	M3	C6	P15	208	53,198	15,663	5,106	74,175	80,828	12,777	93,605	-19,432	2
334	M1	C7	P15	807	89,532	6,509	6,034	102,882	81,317	26,965	108,282	-5,402	2
335	M2	C7	P15	249	66,167	18,382	3,449	88,247	81,450	20,049	101,499	-13,254	2
336	M3	C7	P15	249	59,969	14,182	6,554	80,954	81,713	15,822	97,535	-16,582	1

Appendix E

Groeneveld and Baugh (2002) Report

HYDROBIO
ADVANCED REMOTE SENSIN

Mapping and Estimating Evapotranspiration For Dell Valley, Texas

Prepared for El Paso Water Utility

December 9, 2002

By David P. Groeneveld. Ph.D.
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Executive Summary

Evapotranspiration from groundwater-irrigated agriculture and from playa groundwater discharge was mapped for Dell Valley, Texas. Archived Landsat satellite data from 1974 to 2002 were purchased as the base data for the mapping.

The average for the estimated irrigated area for this period was 21,353 acres, with the maximum of 33,656 acres in 1975, and the minimum of 12,585 acres in 1994. Applying the NRCS irrigation requirement for alfalfa during a normal year yielded 129,877 acre feet/year for 1975 and 48,567 for 1994. Confidence intervals for these acreage estimates are relatively tight: 13 to 20% depending on the number of satellite images used for mapping the year.

Playa discharge was estimated for eight years between 1984 and 2002. The average rate of discharge was 27,430 acre feet/year with a minimum of 12,176 acre feet/year in 2001 and a maximum of 44,089 acre feet/year during 1988. Because of a lack of actual calibration data the confidence interval for this analysis is conservatively large at 100% (pus/minus 50%).

These analyses, data and products have been produced for use in a groundwater model to evaluate the hydrology of Dell Valley being conducted by the City of El Paso.

1. Introduction

Dell Valley, Texas is under evaluation by the City of El Paso for potential future imported water supply. The form of this evaluation is groundwater modeling that requires spatial quantification of evapotranspiration (ET) from crops to enable calculating and distributing groundwater pumping. Significant ET also occurs from valley-floor playas.

The groundwater model for Dell Valley employs square grid cells of 2000 feet on a side. Thus, the relatively fine structure for this regional model requires that the ET data are spatially correct and accurate to the same scale. This report describes the analysis and presents the results for mapping ET at the scale required for accurate spatial modeling.

1.1. Study Area

The Dell Valley region of interest lies approximately 70 miles to the east of El Paso and straddles two states with the greater portion in Hudspeth County, Texas and a smaller piece in Otero County, New Mexico.

There are three types of ET discharge from groundwater in Dell Valley: from irrigation using pumped groundwater, from direct evaporation from the playa, and from the phreatophytes (groundwater using plants) that grow around the margin of the playa. At present, the largest ET discharge is probably from irrigation and all irrigation in the valley is from pumped groundwater. Both irrigation-induced discharge and playa discharge are analyzed in this report. Native phreatophytes, although still a significant water budget component, use much less than irrigation or playa discharge, and are within discrete areas away from the area of greatest interest for the modeling (mostly confined to the eastern side of the playa). The combined regional discharge of groundwater from phreatophytes is probably less than 10,000 acre feet per year (from estimating a continuous canopy cover of about 4 square miles, and a rate of 4 feet/year).

Archived Landsat satellite data were chosen as the base data for mapping ET. Fortunately, data are available for the summer growing seasons from 1974 to 2002. Summertime images were purchased for each summer through this period in order to accurately map annual maximum irrigation. As a secondary application, ET estimates were also made from the playa based upon the summertime data.

The first step in the analysis was to determine the areas where irrigation and playa discharge are located and to divide these areas from the larger region for purposes of analysis. Polygons were mapped of the agriculture region as judged by old field scars or actual crops on the series of images, past and present. The area of interest for playa ET discharge was chosen to be the entire region encompassing playas on the valley floor. By playa, we are referring to alluvially-derived flats that resemble lake bottoms (and possibly are in Dell Valley). In addition to the playas proper, the area of interest of the valley floor also contains significant areas of stabilized dunes that tend to form boundaries of the playas, themselves. These areas are shown on Figure 1.

Figure 1. Overview of the study area. The light polygons enclose irrigated areas, the thick black polygon encloses the playa discharge region, the fine line denotes the Hudspeth County Undergrond Water Conservation District and the two stars denote weather station locations: Dell City 5SSW in the irrigated zone and Salt Flat located near the valley floor playa region.

The interplay between playa discharge and irrigation is an important ET-related factor to understand in Dell Valley. Under pre-irrigation conditions, the vast majority of the ET from the valley probably occurred through the playa since it is the lowest portion of the basin, in essence a "sump". Irrigation has likely diverted a portion of playa discharge. Thus, although irrigation may reduce playa discharge, quantification of the remaining rates of discharge from the playa may be important to an overall understanding of the regional water budget.

1.2 Precipitation

Precipitation within Dell Valley is an important parameter in the ET cycle for several reasons: (1) it is an amount that should be subtracted from the crop use estimates to derive an average annual rate that can be applied to croplands, (2) regional precipitation may cause the rise and fall of local water tables and concomitant fluctuations in playa discharge, and (3) it must be taken into consideration for any estimates of playa discharge since this feature can only be identified by the wetness of the playa surface, a condition potentially highly influenced by antecedent precipitation.

Average annual precipitation is listed for three stations below as reported by El Paso Water Utility (2002).

Table 1. Average annual precipitation at three stations in Dell Valley.

Station	Elevation	Ann. Precip. (in.)
Cornudas Service Station	4,480 feet	9.43
Dell City 5 SSW	3,770 feet	11.15
Salt Flat	3,717 feet	8.48

Precipitation data were purchased from the National Climatic Information Center for Salt Flat, Dell City 5 SSW and Cornudas. The relatively complete data set for Cornudas was analyzed for the period from 1980 to 2000. The percent of the average month's precipitation for the entire year is presented in Figure 2. This pattern shows a very strong mid-summer precipitation peak in August of 25% of the annual total, three times greater than monthly precipitation were it evenly distributed through the year.

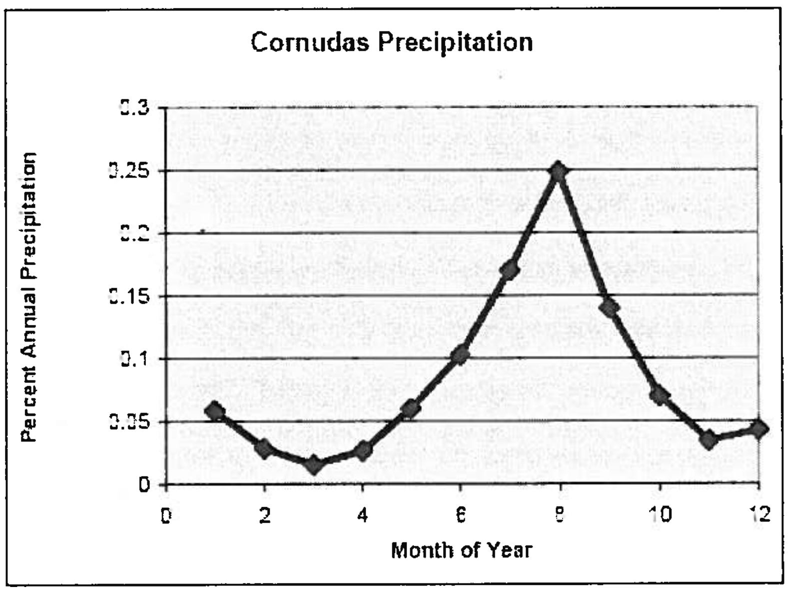

Figure 2. Monthly precipitation at Cornudas Station demonstrates a strong summer monsoon signal for 1980-2000 precipitation. These data were averaged for each month and then converted to percentage of the annual total.

2.0 Field Visit and Aerial Reconnaissance

Dell Valley was visited on July 18, 2002 for airphoto reconnaissance and for evaluation of hydrologic conditions on the playa. Although, this was a brief visit, much information was gained concerning the physical environment that assisted later interpretation of the satellite data.

2.1 Soils and Surficial Deposits

Soils and their water holding capacity are important factors that influence ET in Dell Valley either through upward capillarity from the water table beneath the playa, and through irrigated cropped fields. Soil in agriculture and playa regions were observed in several shallow soil pits. Surprisingly, the texture was uniform, buff colored, silty fine sand for all of the areas evaluated in both the agriculture and playa regions (texture estimated in the field). Although more work would be needed for confirmation, such regional scale massive homogeneous soils suggest aeolian origin.

The interplay of wind and water are responsible for the redistribution and form of the surficial deposits in present day Dell Valley. Gently sloping alluvial fans connect the regional uplifted mountains surrounding the valley with the valley floor. On the valley floor, the very low-relief playa region may have resulted from significant periods of flooding and may represent a relict lake bottom. This overall playa region is broken by dunes, now largely stabilized by vegetation, into smaller playas of variable size from several acres up to about 16 square miles. Because of the similar elevation of the active playas defined among dunal deposits across the playa region, these disjoint features strongly suggest pieces of relict lake bottom. If so, the dunes would be much younger features that have accumulated during recent, dryer times. These interpretations are the basis for conceptualizing playa evaporation: the playas are all hydrologically connected and act as an evaporative surface whose active zones can expand or contract in response to regional patterns of recharge and irrigation pumpage. Their maximal expansion of ET would be ruled by playa area, the inverse of dune-covered areas.

Three shallow soil pits were dug on three widely separated playa pieces. Two of these soil pits disclosed very moist substrate while the third was powdery dry. Interstitial salt lenses of undetermined chemistry were present in all three pits but particularly prominent in the wettest of the three that was located about 500 feet south of the roadway that penetrates the playa region to access the gypsum mine (Figure 3). These salt lenses were indurate, wet and resistant to breakage. The appearance and strength of expression of the salt lenses strongly suggests a sealing action for the fine, silty sand matrix of the playa that otherwise would have relatively high rates of transmissivity. Thus, even with very high internal groundwater pressure, salt enrichment may, in effect, create an "aquitard" that becomes more pronounced toward the surface environment where evaporation concentrates and precipitates the salts. A near surface zone of lower transmissivity would tend to govern rates of upward leakance to supply evaporation.

2.2 Playa Evaporation Indicators

Although the presence and influence of salt lenses requires more confirmation, such interstitial salts could theoretically control playa evaporation through two mechanisms: by moderating upward pressures from the water table, and by providing the capillary forces to raise water from considerable depths (possibly about 10 feet).

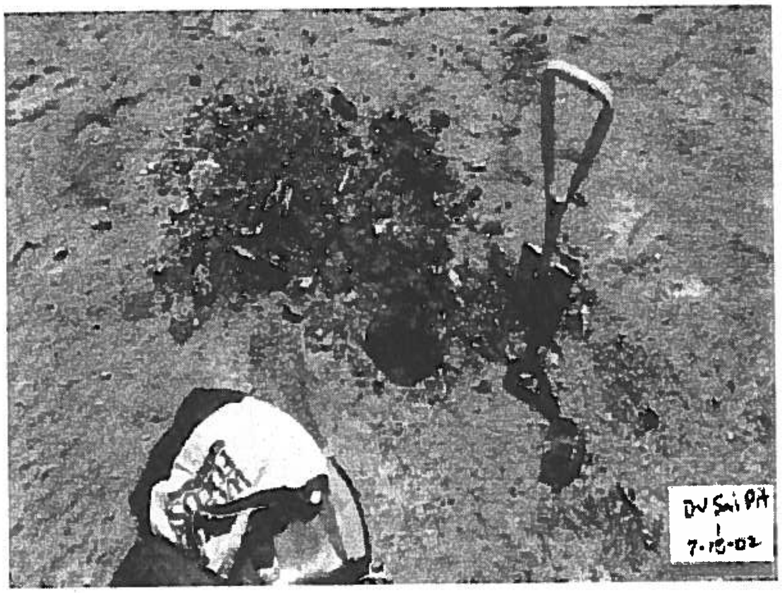

Figure 3. Close up of a soil pit into moist playa substrate. Note the chunks of salt lenses in the spoil pile to the left of the pit. Darker material may be manganese nodules in the salt and substrate matrix. Manganese enrichment is a common feature in shallow water table zones.

Aerial reconnaissance indicated that portions of the playa were actively evapotranspiring at the time of the overflight (7-18-02). Figure 4 is an image of a playa with two indications of active discharge; the presence of a light-colored salt crust on the surface as a halo around the outer edges of the playa and growth of *Allenrolfia* (species unknown), known commonly as pickleweed. The author has noted that pickleweed only grows where the substrate is very wet and connected to shallow groundwater.

Figure 4. Aerial detail of an active playa (to right) with salt efflorescence (lighter colored) and pickelweed (dots) visible. Another piece of a playa is visible at the lower left. The remainder of the scene are dunes raised 10-20 feet above the level of the playa surface.

2.3 Patterns of Irrigation

Aerial reconnaissance disclosed several important considerations for Dell Valley agriculture. As can be seen on Figure 5, Dell Valley cropping is a mix of center pivots and flood irrigation. From aerial observation, flood-irrigated crops today are largely chile but may also include alfalfa while center pivots are largely alfalfa. Chile crops on 7-18-02 were at various levels of canopy closure ranging from widely dispersed, to thick.

Irrigation water in Dell Valley has salt contents that approach 2,000 ppm and the apparent effect of salts, lower irrigation rates or salt buildup are visible in some of the locations near Dell City. Figure 6 illustrates the area east-northeast of Dell City where crops are not as vigorous as in Figure 5. This is an important finding because some portions of fields, though irrigated, have poor vegetation cover that would not be classified correctly if remotely sensed data is used, alone.

Wastewater from flood irrigation generates patterns of plant growth that violate the more-standard appearance cropped and irrigated polygonal fields (as visible on Figures 5 and 6). Wastewater irrigation discharges create shapes like those visible on Figure 7. Thus, for interpretation of irrigated zones on the remotely sensed data, it is important to note that the areas of pumped groundwater ET may constitute shapes other than what would be expected for fields and not necessarily be considered a crop.

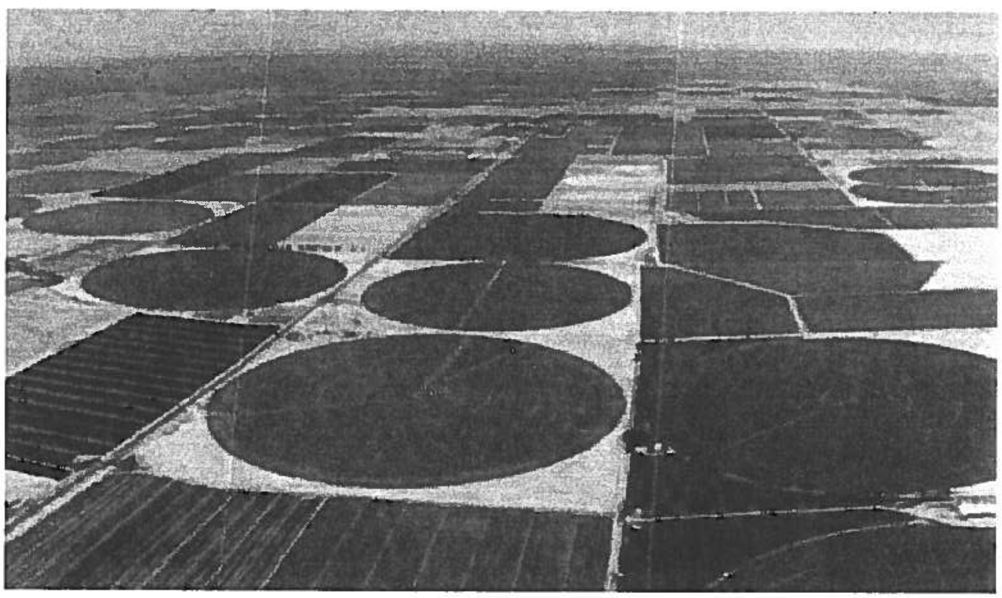

Figure 5. Cropped fields at the south end of the Dell City agriculture area. Center pivots and irrigated fields are both visible. The rectangular-shaped fields in the foregrand and to the left contained chile while the center pivots and the irregular fields to the right appear to be alfalfa (two center-pivot corners at the lower right appear to be chile).

Figure 6. Crops with low levels of vigor to the ENE of Dell City. Some of these fields may be recently cut alfalfa.

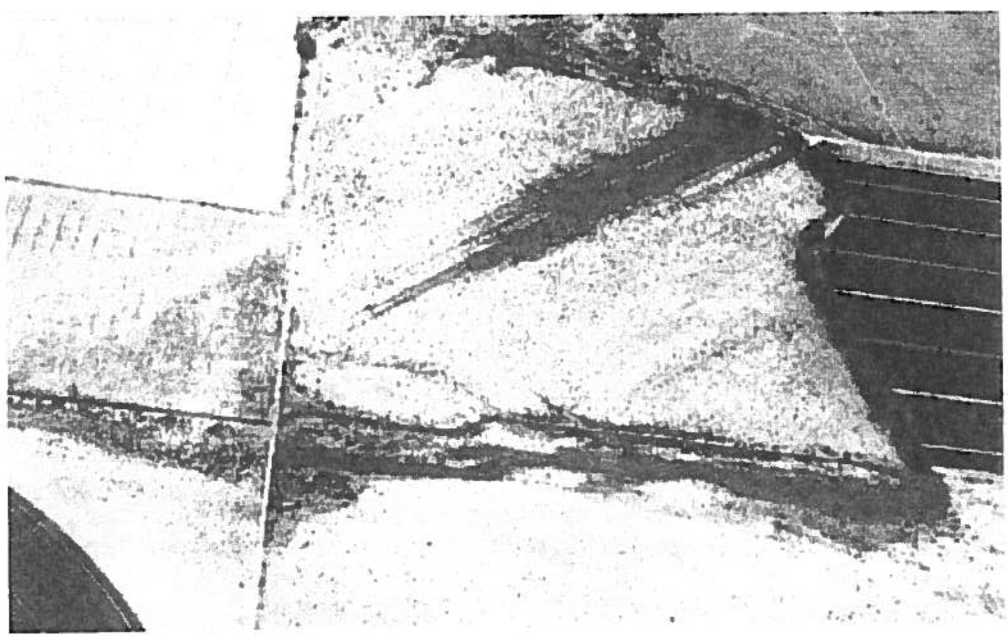

Figure 7. Non-cultivated vegetation enhanced by runoff from fields at the south end of the Dell City agriculture area.

3.0 Evapotranspiration Rates

ET was not measured as part of this study but was adopted from other sources. Rates for irrigation and for playa discharge were developed from separate sources and calculated by different methods. Both methods used satellite data and the interpretations made from it. For ET from irrigated land a single factor is suggested (land is either irrigated or is not). For playa discharge, an estimate of potential ET was used and scaled for reflectance brightness in Landsat TM band 5. This band covers part of the spectrum that is absorbed by water, so increasing water content of a homogeneous substrate such as the playa deposits in Dell Valley appears darker.

Alfalfa constitutes the most commonly grown crop in Dell Valley in recent years with chile a distant second, however, other crops including melons and cotton were grown prior the last decade, or so (James Lynch, personal communication). No attempt was made to account for different rates of water use by crop type. Instead the Blaney-Criddle (TR21) rate quoted by NRCS for Dell City alfalfa, 51.48 inches/year (4.29 feet/year), is suggested for all crops (NRCS Irrigation Water Requirements. Appendix 1). This rate includes effective precipitation, so this needs to be subtracted in order to yield groundwater discharge. Data for irrigation is provided for model input in acres in order to enable evaluating different ET rate scenarios and infiltration returns to the water table, if desired. A calculation is provided in section 4.2 using the "normal year" scenario 46.31 inches/year (3.859 feet/year) of water application required.

Potential ET is the energy limited rate for vegetated surfaces and a reasonably good estimator for rates of loss from continually wetted surfaces. Insufficient data are available to calculate potential evapotransiration in Dell Valley, however, an estimate of maximal ET quoted by Boyd and Kreitler (1986) of 78.7 inches/yr, (6.6 feet/yr) is reasonable given the latitude and summer temperature and humidity characteristic of the Chihuahuan Desert. This figure, again, is total water consumption and precipitation needs to be subtracted to calculate rates of groundwater discharge. Potential ET rates were scaled against reflectance in band 5 to estimate annual rates.

4.0 Mapping Irrigation

4.1 Method of Analysis

Landsat data were purchased for the growing season for the period 1974 to 2002, excluding 1978, 1989 and 1993. These data are shown in Table 2. All satellite images were geocorrected and then radiometrically corrected to yield reflectance (NASA, undated). Appendix 2 contains technical notes on preparation and analysis of these data.

The remote sensing technique for identification of irrigated lands was simple. Where water is applied to the land to grow a crop, plant cover becomes sufficiently verdant to be easily distinguishable from the surrounding desert that receives only an annual average of about nine inches supplied by precipitation directly. Normalized difference vegetation index (NDVI) was chosen to map relative vegetation activity to enable selection of a cutoff level for NDVI above which all included lands are irrigated. NDVI uses a ratio of the bands in the red and the near infrared (NIR):

$$\text{NDVI} = \frac{\text{NIR-Red}}{\text{NIR+Red}}$$

NDVI can be calculated from both TM and MSS data: for TM, bands 3 and 4 are used and for MSS, bands 5 and 7. All of the data prior to 1984 were MSS and have a pixel size of 57 m^2 (0.80 acre). TM data were obtained from 1984 to 2002. These have a pixel size of 28.5 m^2 (0.20 acre).

Table 2. Satellite data purchased for analysis of irrigation and playa discharge. Years with three dates of images are listed in the right-hand columns

Year	Sensor	Path/Row	Date	Cloud	Year	Sensor	Path/Row	Date	Cloud
2002	TM7	32/38	25-Jun	n					
2001	TM7	32/38	8-Jul	n					
2000	three dates of imagery:				2000	TM5	32/38	14-Aug	n
1999	TM5	32/38	12-Aug	n		TM5	32/38	13-Jul	n
1998	TM5	32/38	25-Aug	n		TM5	32/38	11-Jun	n
1997	TM5	32/38	5-Jul	n					
1996	three dates of imagery:				1996	TM5	32/38	19-Aug	n
1995	TM5	32/38	2-Sep	y		TM5	32/38	2-Jul	n
1994	TM5	32/38	13-Jul	y		TM5	32/38	16-Jun	n
1993	missing								
1992	three dates of imagery:				1992	TM5	32/38	23-Jul	y
1991	TM5	32/38	6-Aug	n		TM5	32/38	7-Jul	n
1990	TM5	32/38	19-Aug	n		TM5	32/38	21-Jun	n
1989	missing								
1988	three dates of imagery:				1988	TM5	32/38	13-Aug	y
1987	TM5	32/38	10-Jul	n		TM5	32/38	12-Jul	n
1986	TM5	32/38	23-Jul	y		TM5	32/38	10-Jun	n
1985	TM5	32/38	4-Jul	n					
1984	TM5	32/38	17-Jul	n					
1983	three dates of imagery:				1983	MSS4	32/38	25-Sep	n
1982	MSS3	34/38	31-Oct	n		MSS4	32/38	5-Jun	n
1981	MSS2	34/38	11-Jul	n		MSS4	32/38	4-May	y
1980	MSS2	34/38	3-Aug	n					
1979	three dates of imagery:	34/38	31-Jul	y	1979	MSS3	34/38	11-Oct	n
1978	missing					MSS2	34/38	18-Aug	n
1977	MSS2	34/38	12-Sep	n		MSS2	34/38	31-Jul	n
1976	MSS2	34/38	15-Aug	n					
1975	three dates of imagery:				1975	MSS1	34/38	26-Sep	n
1974	MSS2	34/38	21-Jul	n		MSS2	34/38	28-Jun	n
						MSS1	34/38	5-May	n

NDVI functions well as an identifier of plant activity and its water use. Figure 8 shows an illustration of the reflectance through the red edge region, the part of the spectrum between visible and near infrared light. Growing vegetation is green only because it reflects the light in the green portion of the visible spectrum: virtually all of the red light is absorbed by chlorophyll to power photosynthesis. Leaf tissue reflects very highly in the near infrared and so the normalized ratio of red to near infrared in NDVI becomes a powerful predictor, both of vegetation activity, and its water use.

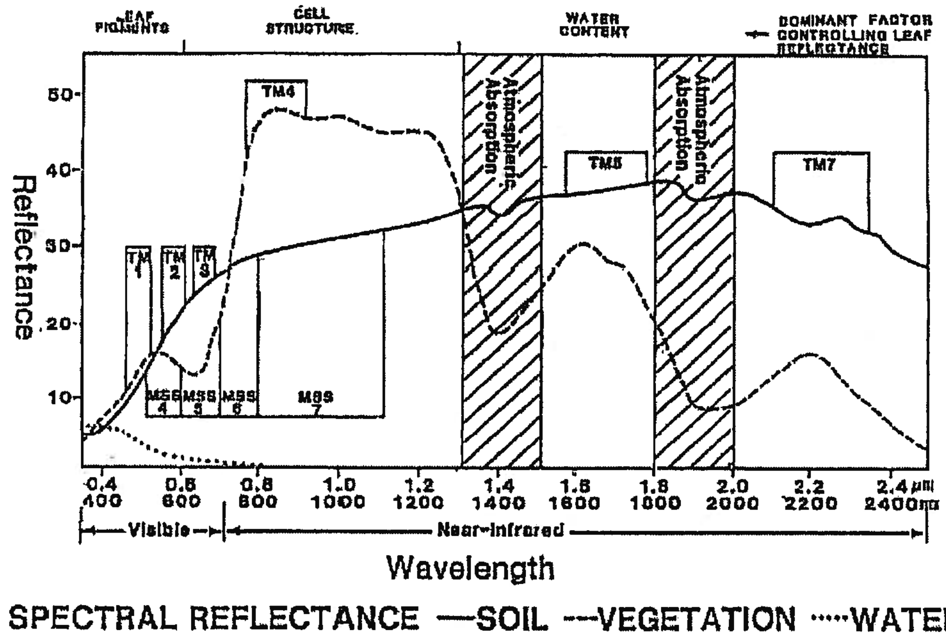

Figure 8. A schematic of reflectance for soil, vegetation and water superimposed with Landsat MSS and TM bands. The red edge is covered by TM bands 3 and 4 and by MSS bands 5 and 7: these bands are used to calculate NDVI. TM band 5 was used to map playa ET discharge.

Irrigated areas were mapped from satellite data first by employing an NDVI threshold, some level of NDVI brightness above which all pixels are classified as irrigated. This works because there is generally a large difference in NDVI between the irrigated crop and the surrounding vegetation of the Chihuahuan desert landscape. The threshold was placed high enough to exclude this native vegetation or weeds supported by incident precipitation. Even so, a significant number of images contained some relatively verdant vegetation that was not irrigated, for example, episodically for native vegetation growing in washes during a very wet summer, and continuously for the vegetation within a band located on the east side of the valley at the foot of the Guadalupe massif. The analysis of irrigated land using NDVI was delimited to the zone shown on Figure 1 to control error induced by vegetation that was not of interest. Though the initial NDVI-threshhold-based classification used this boundary, the subsequent analysis added irrigation outside if warranted.

Each of the years analyzed for irrigated area was represented by either one or three dates of imagery. Initially, the plan for analysis was to use the three dates of imagery to develop correction factors to adjust the single dates of imagery upward to account for low NDVI that may occur even though a field is irrigated, e.g., recently cut alfalfa, temporary fallowing, etc. However, because of the requirement to adjust the NDVI cutoffs to relatively high levels to avoid native and weedy vegetation in mid- to late-Summer scenes, particularly for years with significant monsoon precipitation, this technique was abandoned in favor of adding a quasi-photo-interpretive step to identify additional fields after using an NDVI cutoff to find the majority of the irrigated fields.

During the course of this study, and from earlier observations for 2001 data, we learned that significant areas of irrigation may not be counted because of (1) alfalfa having been recently cut, (2) recently-cultivated with little canopy development at the time of the satellite overpass, (3) being freshly irrigated and having low, or no, crop canopy, or (4) a "scald" spot within a field possibly caused by poor soil structure or irrigation-induced salt buildup. These added areas varied from an estimated few percent to up to 35%. Because of this under counting, each of the satellite images was subjected to manual interpretation in Arcview. Areas excluded by the conservative NDVI threshold were identified as irrigated if they (1) were obviously part of a polygonal field that did have some pixels with NDVI above the threshold, (2) had signatures and patterns that indicated irrigation, or (3) had NDVI response significantly above the background desert and were confined to polygons (unequivocally in the case of center pivots). The NDVI classified areas on the three-date years were combined before undertaking interpretive mapping and thus, the three dates helped to reduce uncertainty.

4.2 Results and Products for Mapping Irrigation

Observations of crop phenology were made during the analysis. Much of the crop cover that is visible later in the growing season is only poorly visible until late June, presumably because canopy closure has proceeded far enough to induce an NDVI response that is above the NDVI cutoff level set to avoid non-irrigated cover or weedy vegetation. The general progression of seasonal phenology was observed on the three-per-year data sets. From these observations, the least uncertainty for identifying irrigated area from a single growing season image was for mid- to late August data. This appears to be related to the maximal expression of the pre-harvest crop canopy for non-alfalfa crops (mostly chile) while, at the same time, identification of recently-cut alfalfa does not pose that great a difficulty for positive identification since it generally occupies a polygonal field and has an NDVI response significantly above the background. Unfortunately, weedy vegetation responding to the highest precipitation period (August) may confound this relationship.

In addition to plant vigor and phenology, dark polygonal areas were taken to be an indicator of irrigation. Dark regions placed within the agriculture zone are accurate indicators of irrigation because the country soil is generally dry, highly reflective in most wavelengths and has very low reflectance in all wavelengths when flooded or wetted. An interesting trend was apparent during analysis. The area with evident surface irrigation increased dramatically for September and October suggesting either, or both. pre-season irrigation or application of a leaching fraction to flush salts from the soil.

The results of the analysis are shown on Figure 9 and in Table 3. Because of relatively liberal classification, the estimate of irrigated land is probably slightly biased toward higher acreage rather than lower.

Table 3. Total Dell Valley irrigated acreage by year with a listing of the sensor used to gather the data and whether the analysis was for multiple or single years.

Year	Acres	Mode	Sensor	Year	Acres	Mode	Sensor
1974	29825	single	MSS	1988	19169	multiple	TM
1975	33656	multiple	MSS	1990	16873	single	TM
1976	26410	single	MSS	1991	16767	single	TM
1977	32810	single	MSS	1992	13847	multiple	TM
1979	29422	multiple	MSS	1994	12585	single	TM
1980	30930	single	MSS	1995	16388	single	TM
1981	22249	single	MSS	1996	18581	multiple	TM
1982	27923	single	MSS	1997	16149	single	TM
1983	18529	multiple	MSS	1998	19526	single	TM
1984	16807	single	TM	1999	19246	single	TM
1985	16657	single	TM	2000	21651	multiple	TM
1986	20333	single	TM	2001	21660	single	TM
1987	17692	single	TM	2002	19327	single	TM

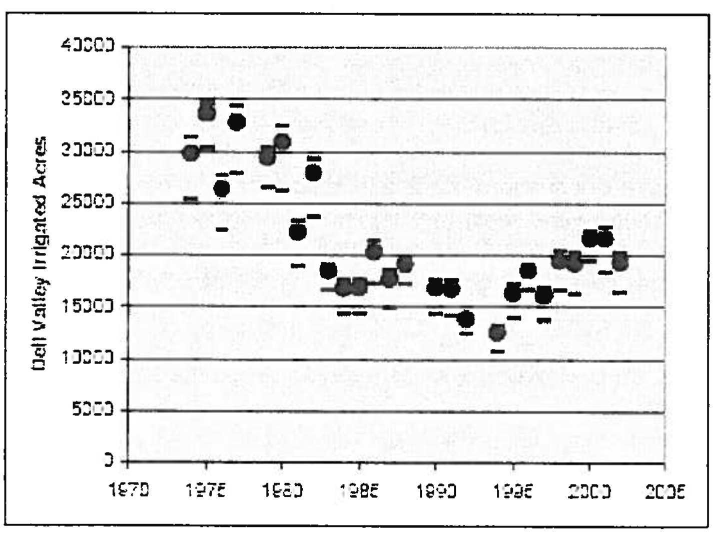

Figure 9. Irrigated acreage in Dell Valley by year. Dots denote best estimate and bars indicate potential maximum and minimum taking into account the uncertainties in the methods used.

No data sets are available to enable cross checking the results of acreage estimates, however, the results all appear to be reasonable and compare favorably among years. Since the estimated acreage was pushed toward the maximum, the potential maximum is a smaller interval than for the minimum. Uncertainty for the acreage mapped was estimated to be within plus 3% and minus 10% for years with three images per year and plus 5% and minus 15% for single-image years. Accuracy for identification of irrigated areas is generally better for TM over the MSS data due to increased quality for more recent images and higher resolution of the pixels (4x area). However, this difference was not estimated.

Finally, taking the unbounded estimate of irrigated acreage from Table 3 and applying the 3.859 feet per year irrigation requirement yields the estimated applied water within the Dell Valley region for each year mapped (Table 4).

Table 4. Application of the annual alfalfa irrigation requirement reported by NRCS to estimate the irrigation requirement for Dell Valley crops.

Year	Acre Feet/yr	Year	Acre Feet/yr	Year	Acre Feet/yr	Year	Acre Feet/yr
1974	115,093	1982	107,754	1990	65,111	1998	75,349
1975	129.877	1983	71,426	1991	64,704	1999	74,272
1976	101,917	1984	64,959	1992	53,437	2000	63,552
1977	126.615	1985	65.050	1994	48,567	2001	63,564
1979	113.538	1986	78,465	1995	63,239	2002	74,582
1980	119.359	1987	68,274	1996	71,706		
1981	85.860	1988	73,972	1997	62,318		

5.0 Mapping of Playa ET Discharge

As a caveat, it must be stressed that although the analysis of playa discharge is logical and follows theoretical constraints, it is also somewhat subjective because no evaporation data are available on which to calibrate or cross check the band 5 response. Because of this, error bars associated with the spatial estimates were set at a relatively conservative plus minus 50%.

A confounding factor to mapping playa discharge is the satellite data that were obtained for mid-summer conditions to optimize for the analysis of irrigation. Unfortunately, playa discharge likely has a periodicity that peaks in the spring, since it is rate-limited by substrate and groundwater pressures. As temperatures and daily solar radiation load increase through spring and into summer, large areas of playa discharge are probably overwhelmed and dry out due to increasing atmospheric evaporative drive.

5.1 Remote Sensing Method

Landsat TM band 5 is highly sensitive to water and was used to provisionally map evaporation from the playa. Band 5 is a feature only of TM and not MSS and so, can only be applied to data from 1984 to 2002.

No data sets are available to enable cross checking the results of acreage estimates, however, the results all appear to be reasonable and compare favorably among years. Since the estimated acreage was pushed toward the maximum, the potential maximum is a smaller interval than for the minimum. Uncertainty for the acreage mapped was estimated to be within plus 3% and minus 10% for years with three images per year and plus 5% and minus 15% for single-image years. Accuracy for identification of irrigated areas is generally better for TM over the MSS data due to increased quality for more recent images and higher resolution of the pixels (4x area). However, this difference was not estimated.

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5.1 Remote Sensing Method

Landsat TM band 5 is highly sensitive to water and was used to provisionally map evaporation from the playa. Band 5 is a feature only of TM and not MSS and so, can only be applied to data from 1984 to 2002.

As an initial confirmatory analysis, a subset of eight of the TM images was analyzed to determine whether antecedent precipitation affected band 5 reflectance: it did, highly. Virtually all surfaces wetted by recent rains had very low reflectance and it was not possible to differentiate dunal materal and uplands from the playa surface—all were wet and had low reflectance. Thus, only the satellite data subset that experienced dry antecedent conditions could be used. Precipitation records and TM data sets chosen for analysis due to dry antecedent conditions are listed in Table 5.

Table 5. Antecedent precipitation at three weather stations for all TM images. The highlighted entries were chosen as the subset for analysis.

Image No.	2 day	Cornudas 5 day	10 day	2 day	Dell City 5SSW 5 day	10 day	2 day	Salt Flat 5 day	10 day
840717TM	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00	0.00
850704TM	na	na	na	0.00	0.00	0.06	0.00	0.00	0.00
860723TM	0.03	0.33	0.38	0.00	0.19	0.19	0.00	0.00	0.00
870710TM	0.33	0.30	0.00	0.03	0.00	0.00	0.00	0.00	0.00
880610TM	0.00	0.00	0.00	na	na	na	0.00	0.00	0.00
880712TM	0.00	0.97	1.83	0.83	0.95	1.74	0.57	0.80	0.83
880813TM	1.25	2.78	2.93	0.41	1.00	1.49	0.00	0.53	1.06
890613TM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
900819TM	0.00	0.67	0.67	0.06	2.02	2.37	0.03	0.80	0.80
910806TM	0.15	0.22	0.80	0.00	0.98	2.11	0.00	0.44	0.51
920621TM	0.17	0.17	0.17	0.00	0.00	0.00	0.00	0.00	0.00
920707TM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
920723TM	0.00	0.57	0.57	0.00	0.18	0.60	0.00	0.00	0.08
920808TM	0.08	0.10	0.87	0.62	0.62	0.62	0.00	0.15	0.15
930624TM	0.00	0.00	0.00	0.06	0.13	0.20	0.05	0.30	0.31
940713TM	0.20	0.20	0.20	0.00	0.00	0.00	0.00	0.00	0.00
950922TM	0.00	0.00	0.00	0.07	0.07	0.07	0.00	0.00	0.00
960616TM	0.00	0.44	0.44	0.51	1.86	1.86	0.50	1.25	Na
960722TM	0.00	2.26	2.41	0.00	1.56	2.06	0.00	2.40	2.75
960814TM	0.00	0.00	1.05	0.00	0.00	0.52	0.00	0.00	0.70
970726TM	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.38	0.38
980825TM	0.00	0.00	0.00	0.00	0.00	0.00	na	na	Na
990812TM	0.00	0.00	1.65	0.10	0.00	1.78	na	na	Na
000611TM	0.00	0.00	1.28	0.00	0.00	1.33	na	na	Na
000713TM	0.00	0.03	0.03	0.00	0.35	0.43	na	na	Na
000814TM	0.00	0.75	0.75	0.00	0.65	0.95	na	na	Na
010608TM	Na	na	na	0.00	0.00	0.00	na	na	Na
020609TM	Na	na	na	0.00	0.00	0.00	na	na	Na

The first step in the analysis for Band 5, like for the red and near infrared bands, was to perform radiometric and geometric correction of the imagery. The next step was to determine a threshold for band 5 to distinguish moist regions of the playa from surrounding dune deposits. This level was uniformly about 0.30 reflectance units. An example of a classification within this cutoff is shown on Figure 10.

Within the identified playa zones such as that shown on Figure 10, the reflectance of band 5 varied from .30, at the driest end, to 0 at the wettest end. A set of histograms for the recent years of the TM subset and for only the playa regions identified are shown on Figure 11. These histograms aid selection of the cardinal ponts for ET: these are 0.18 at the low end 0.3 at the high end.

Figure 10. Playa zones on the July 4, 1985 TM data differentiated at a band 5 threshold reflectance level of approximately 0.30. Dunes constitute the features to the right of the large ca. 16 square mile playa area shown. Irrigated acreage surrounding Dell City is visible to the left.

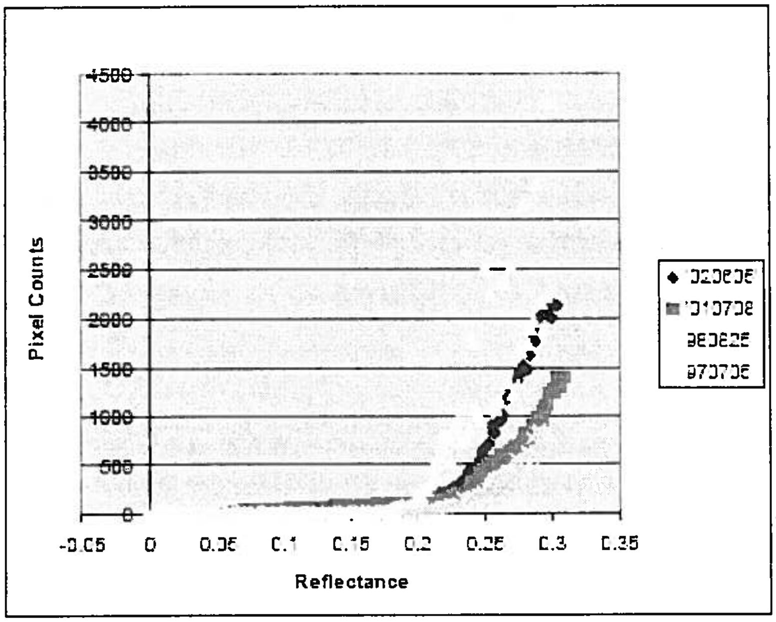

Figure 11. Histograms of four years of band 5 data. The cutoff at 0.3 reflectance was necessary to distinguish the playa from the upland dunes on all images. Likewise, all images had relationships that went asymptotic at about 0.18.

5.2 Apportioning Playa Evaporation

The ETp for Dell Valley was taken to be 78.7 inches/yr (6.56 feet/yr; Boyd and Kreitler, 1986) from which precipitation must be subtracted to calculate groundwater discharge. Since the playas are widely distributed on the valley floor, the long-term average precipitation for the three stations of Table 1, 9.7 inches was used to adjust ETp to yield discharge from groundwater: 69 inches (5.75 feet).

The potential groundwater discharge component of playa evaporation, 5.75 feet, then used the cardinal points to develop the relationship that was applied to the entire playa discharge region:

Spectral Response	Evaporation Rate
<0.18 reflectance	maximum – 5.75 feet/year
0.18 to 0.30 reflectance	linear relationship: 14.375 – 47.917 * reflectance
> 0.30 reflectance	zero discharge from groundwater

5.3 Estimates of Playa Groundwater Discharge

The total estimated groundwater discharge from Dell Valley playas is presented in Table 6. These estimates vary from a low of about 12,000 acre feet in 2001 and 2002 during a prolonged regional drought, and 44,000 acre feet following a series of very wet years.

Table 6. Values for playa discharge calculated using band 5 and the relationships defined by cardinal points.

Year	Pixels	Area of Discharge (Ac)	Discharge (AF/yr)	Av. Rate (ft/yr)
2002	44,052	8,837	12,472	1.41
2001	27,684	5,553	12,176	2.19
1998	62,887	12,615	25,835	2.05
1992	64,837	13,006	26,282	2.02
1989	42,520	8,533	19,662	2.31
1988	90,080	18,070	44,089	2.44
1985	70,696	14,182	40,101	2.83
1984	80,281	16,104	38,652	2.41

The general concurrence for these snapshots suggests that the method tracks regional patterns of recharge: low during intensive regional drought, and high during intensive regional wet. This was checked by graphing the estimates of ET against the antecedent precipitation for the prior two water years (back to October 1) measured at Dell City 5SSW. This is shown on Figure 12.

There are a number of indications that the methods used here to estimate ET discharge are tracking Playa ET correctly. The strong concurrence between the low playa discharge estimates for 2001 and 2002 concur with late years in a multi-year regional drought: water pressures beneath the playa have probably been reduced to a minimum. Another corroboration is the positive relationship of the estimated total playa discharge and the regional precipitation. That the data appear two-ranked may be an indicator that, although Dell City precipitation is a competent indicator of regional precipitation, there are much larger patterns of recharge that it does not capture. The early-to-mid-1980's are known throughout the Southwest as a relatively wet period while the late 1990's into summer, 2002 are known as a significantly dry period.

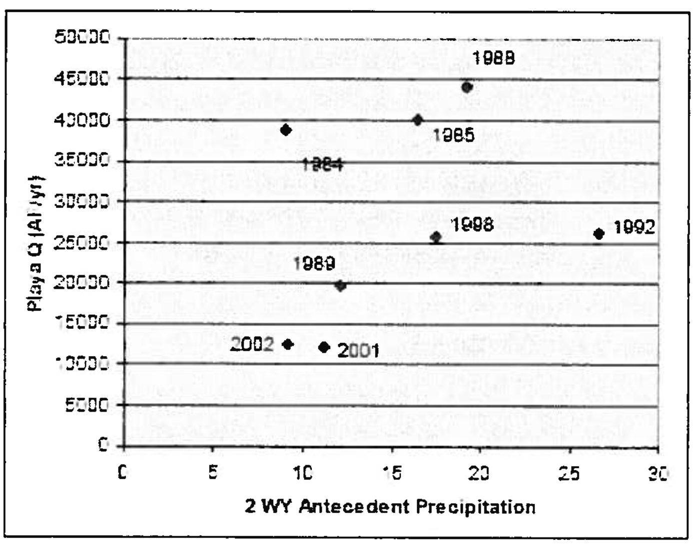

Figure 12. Calculated total playa groundwater discharge graphed against total Dell City precipitation. This precipitation sum is intended as a general indicator of regional recharge that is positively correlated to playa discharge. The data appear two-ranked possibly following droughty, 1988-2002, and wet, 1984-1988, regional conditions.

These playa estimates are translated into a best estimate and error bound of plus/minus 50% in Table 7. The reason for the large error bound is a lack of actual calibration. Calibration would require knowing the substrate at least qualitatively, substrate water content, ET, and reflectance in Band 5.

Table 7. Total Dell Valley playa discharge and error bounds in acre feet/year.

Year	Less 50%	Best Estimate	Plus 50%
2002	6,236	12,472	18,708
2001	6,088	12,176	18,264
1998	12,902	25,805	38,707
1992	13,141	26,282	39,423
1989	9,831	19,662	29,493
1988	22,045	44,089	66,134
1985	20,050	40,101	60,151
1984	19,426	38,852	58,278
Average	**13,715**	**27,430**	**41,145**

Appendix 1.

Irrigation Water Requirements
Crop Data Summary

Job: **Dell City**
Location: Dell City
By: Walker
Weather Station: CORNUDAS SERVICE STN
Latitude: 3147 Longitude: 10526
Computation Method: Blaney Criddle (TR21)
Crop Curve: Blaney Criddle Perennial Crop
Begin Growth: 3/7 End Growth: 11/8

Crop: **Alfalfa Hay**
County: Hudspeth, TX
Date: 03/07/02
Site No: TX2912
Elevation: 4480 feet above sea level

Net Irrigation application 1 inches
Estimated carryover moisture used at season.
Begin: 0 inches End: 0 inches

Month	Total Monthly ET (3) inches	Dry Year 80% Chance (1) Effective Precipitation inches	Dry Year 80% Chance (1) Net Irrigation Requirements inches (2)	Normal Year 50% Chance (1) Effective Precipitation inches	Normal Year 50% Chance (1) Net Irrigation Requirements inches (2)	Average Daily ETc inches	Peak Daily ETPk inches
January	0.00	0.00	0.00	0.00	0.00	0.00	
February	0.00	0.00	0.00	0.00	0.00	0.00	
March	1.60	0.04	1.56	0.06	1.54	0.07	
April	4.22	0.07	4.15	0.10	4.12	0.14	0.18
May	7.00	0.21	6.79	0.30	6.70	0.23	0.28
June	9.58	0.53	9.05	0.75	8.83	0.32	0.40
July	10.21	0.76	9.45	1.08	9.13	0.33	0.43
August	8.64	1.02	7.62	1.45	7.19	0.28	0.36
September	6.07	0.66	5.41	0.94	5.13	0.20	0.26
October	3.70	0.32	3.38	0.45	3.25	0.12	0.14
November	0.45	0.02	0.43	0.03	0.42	0.09	
December	0.00	0.00	0.00	0.00	0.00	0.00	
TOTAL	51.48	3.63	47.84	5.16	46.31		

(1) For 80 percent occurrence, growing season effective precipitation will be equaled or exceeded 8 out of 10 years. For 50 percent chance occurrence, effective precipitation will be equaled or exceeded 1 out of 2 years.

(3) ET Evapotranspiration) is adjusted upwards 10% per 1000 meters above sea level.

Date 03/07/02

Appendix 2. Technical Notes for Processing Dell Valley Images

A.0 General information:
Image processing was performed using the Environment for Visualizing Images (ENVI) software. This software is based on the Interactive Data Language (IDL) and is sold by Research Systems Inc. (RSI, Boulder, CO). ENVI software can be customized to perform specialized tasks by writing programs in IDL.

Two types of satellite imagery were used, both from the Landsat satellite. The Multi-Spectral Scanner (MSS) is an older style sensor that produces 187 foot (57 m) pixels, and has 4 spectral bands covering the wavelength range from 0.55 to 0.95 micrometers. The Thematic Mapper (TM) sensor is a newer style sensor that produces 93.5 foot (28.5 m) pixels, and has 6 spectral bands covering the wavelength range from 0.485 to 2.215 micrometers. (It also has a lower resolution thermal band that detects energy at 11.45 micrometers.) There have been a series of Landsat satellites. Landsats 1-3 had only the MSS sensor, Landsats 4-5 had MSS and TM sensors, and Landsat 7 has only the TM sensor. (Landsat 6 failed.)

A.1 Image quality check:
Landsat imagery was checked for quality when shipments were received from the EROS Data Center (EDC). Severe quality problems were encountered with the older Landsat MSS imagery – primarily from the Landsat 2 satellite. In most cases, the data values were saturated to 100% and useful information could not be recovered. The EDC suggested that the bright desert areas were saturating the detectors on the satellite. Nine MSS images were returned to the EDC for replacement with similar images of better quality. One Landsat TM image was returned for replacement due to non-systematic geometric distortions. These distortions could not be corrected by standard geometric correction techniques.

A.2 Geometric correction:
Satellite images were geometrically corrected to fit the State Plane projection for the Texas Central Zone (4203) using the NAD 83 datum. The correction was done with a method known as polynomial warping. On the satellite images distinct locations, such as road intersections, were located and the corresponding map coordinates were found using 1:100,000 scale USGS Digital Line Graphs (DLG). Approximately 25 of these Ground Control Points (GCP) were selected for each image. The image processing software performed the warp using the GCPs, and second order polynomial equations. Our standard for spatial error was better than 0.5 pixels Root Mean Square (RMS) error. In most cases, RMS was 0.3 to 0.4 pixels. Satellite images were processed for an area bounded by a box with the upper left corner = 664250E, 10877950N and the lower right corner = 944762E, 10457182N (State Plane, TXC83).

A.3 Radiometric correction:
TM and MSS digital numbers (raw data) were converted to reflectance units using published post-launch gains and offsets, and solar illumination geometry (Landsat 7

Science Data Users Handbook, Technical Notes, http://ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html)

For all images, a regression adjustment (dark object subtraction) was used to correct for atmospheric effects (Jensen 1986, Chavez 1988).

A.4 NDVI calculation:
Normalized difference vegetation index (NDVI) was calculated for all the images using reflectance data and the formula: (IR – Red) / (IR – Red). For TM data, IR is band 4 and red is band 3. For MSS data, IR is band 4 and red is band 2.

A.5 Irrigation analysis:
Irrigated lands were identified using NDVI images. A threshold was chosen by inspection to separate irrigated and barren land. Additional irrigated areas that were not entirely selected by the NDVI analysis were filled manually.

A.6 Wet area analysis:
Wet playa areas were mapped using Landsat TM band 5 images. Band 5 is centered at 1.65 micrometers, a wavelength that is absorbed by water. Lower values in band 5, therefore, correspond with increasing amounts of water. Wet areas were initially identified by adjusting a threshold of band 5 up and down so that wet areas were included, but adjacent dunes were excluded. Inspection of the histograms of the selected wet areas revealed consistent patterns. The patterns were used to develop a 3-step assignment of water discharge based on the reflectance value of the band 5 pixels.

A.7 Automation:
Programs were written in IDL to automate the image processing procedures. The advantage is to assure consistency in processing numerous images, and to facilitate making changes or updates to the entire set of images. GCPs were selected by hand, and all aspects of processing, such as radiometric gains and offsets and dark object subtraction values, were printed to log files and checked manually. Programs were written to aggregate the satellite image pixels into the larger grid cells specified for this project.

Literature Cited:

Boyd, F.M., C.W. Kreitler. 1986. Hydrogeology of a gypsum playa, northern Salt Basin. Texas. University of Texas, Bureau of Economic Geology. Report of Investigation No. 158. 37 pp.

Chavez. P.S., 1988, An improved dark-object subtraction technique for atmospheric scattering correction of multispectral data. Remote Sensing of Environment, v. 24, p. 459-479.

El Paso Water Utilities. 2002. Conceptual model of the groundwater flow system Bone Spring-Victorio Peak Aquifer, Salt Basin and Diablo Plateau, Hudspeth and Culberson Counties. Texas. Peer Review Draft, EPWU Hydrogeology Report 02-02.

Jensen, J.R., 1986, Introductory digital image processing, a remote sensing perspective: Prentice Hall, Englewood Cliffs, NJ. 379 p.

NASA. undated. Landsat 7 Handbook. Available online at: http://itpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html)

Appendix F

Comments to Draft Report and Responses to Comments

Huff HydroResources

220 Astor Drive, Las Cruces, NM 88001
_Phone: 575-526-1884, E-mail: rick_huff@zianet.com_

Date : April 11, 2008

To : William R. Hutchison, Ph.D., P.E., P.G.

From: G.F. Huff

Re: Technical review of the report 'Preliminary groundwater flow model Dell City area, Hudspeth and Culberson Counties, Texas', EPWU Hydrology Report 08-01, in partial fulfillment of contract MCHUFFHYDROR08.

Bill,

I have reviewed the subject report and found it to be a very good piece of work. My comments are divided into those specific to a given part of the text or a selected figure and those of a more general nature. Your model represents a significant step forward in the quantitative representation of the hydrology of the Salt Basin.

Specific comments:

H1-1 Figure 4 – Location of the Guadalupe and Delaware Mountains should be shown on figure 4.

H1-2 Page 7 – The last sentence in section 2.1 should be moved to be the first sentence on page 6.

H1-3 Page 14 – Sentence starting with 'Reed (1965, pg. 18)' includes the text 'recharge to the area above a **depth** of 700 feet'. Not sure what this means.

H1-4 Page 15, section 3.6, second paragraph – 'flow down the structural dip of a monocline' is mentioned but there is no prior discussion of this monocline. Sentence needs some context.

H1-5 Page 24, figure 14 – The symbols on this figure are difficult to differentiate. If it's a copy of an original from Eastoe and Hibbs (2005) we may be stuck with it. However, if you generated the figure yourself you may want to consider using a greater variety of symbols. Also, axes need to be labeled with units of per mil (o oo).

H1-6 Page 33, section 4.4, paragraph 2 – Some things to consider in this paragraph. WhileDell City water could be explained by relatively unevaporated Diablo Plateau water it is not dissimilar to Sacramento Mountains water as shown in figure 14. While water in the Dell City area certainly could have a Diablo Plateau component there also may be alternate explanations such as the possibility that runoff from summer rainfall on the Diablo Plateau may reach the Dell Valley area via surface runoff and infiltrate there. I'm a bit H1-6 bothered by the fact that the Dell City area water doesn't show more of an evaporation trend on fig. 14 than it does considering that the Eastoe and Hibbs (2005) abstract states that the Dell City sample were taken from 'basin fill'. Do they mean the limestone aquifer or the alluvium covering the limestone aquifer in Crow Flats/Dell Valley? You are more familiar with the Eastoe and Hibbs (2005) work than I so please let me know if I'm missing something. The upshot is that you may consider softening your interpretation somewhat in this paragraph.

H1-7 Page 36, sentence 1 – You may want to qualify return flow as 'current or modern' here as I am assuming a 2002 study would primarily discuss return flow as a fraction of irrigation applied using sprinkler systems rather than flood irrigation.

H1-8 Page 36, section 4.6, paragraph 1, sentence 1 – 'Hydraulic properties of the aquifer are parameters that describe the **rate of movement** and storage properties of the **aquifer**.'

H1-9 Page 36. section 4.6. paragraph 1, sentence 5 – Replace 'flow rate' with 'flux'.

H1-10 Page 36, section 4.6, paragraph 2, sentences 2-4 – Heterogeneity means that aquifer properties vary spatially.

H1-11 Page 41, section 4.8 – Were the Blair estimates of return flow based on the assumption of sprinkler irrigation, flood irrigation, or some combination of the two?

H1-12 Page 50, section 5.2, paragraph 5 – Is the table 29 referenced here actually table 9. While the observations of Huntoon (1995) may be correct is there not also a bias in the other direction in that most tested wells wind up being 'good' wells that are located in highly conductive parts of the aquifer?

H1-13 Page 53, figure 27 – Would it be worthwhile to have a figure actually showing the model grid?

H1-14 Page 53, section 6.1, paragraph 2 – I assume the model rotation was to align the grid with the regional trend in anisotropy. Is so, consider a sentence to explicitly state the reason for the model rotation.

H1-15 Page 60, paragraphs 4 and 5 and page 61, paragraph 1 – Identify 'zones' as 'irrigation pumping zones'.

H1-16 Page 75, section 6.3.6 – Specify Groenveld and Baugh estimate to be an estimate of ET under 2002 conditions if applicable.

H1-17 Page 74, figure 32 and Page 76,figure 34 tables – Specify boundary conductance in tables as boundary transmissivity as given units are in ft²/day.

H1-18 Page 78, sentences 12-14 – Unclear as to how steady state recharge was determined. Average of 1948-1973 precipitation data?

H1-19 Page 88, sentences 1-3 – One of these 'western' boundaries needs to be an 'eastern' boundary.

H1-20 Page 99, paragraph 1 – Include some variation of this paragraph in an earlier part of the report. This explains a lot about questions I originally had on pages 74-78 on things like how T values at boundary heads were determined and why they varied between models and why something as apparently fundamental as cell elevation varied between the three models.

H1-21 Section 7.1 starting on page 99 – In order to use standard deviation in this sense you need to demonstrate that you cannot reject the null hypothesis of a normal distribution of residual errors. For a quick and powerful test for normality see Looney and Gulledge (1995).

H1-22 Also, a figure showing the spatial distribution of steady state residual errors would be useful. [Note: This looks like a very solid calibration.]

H1-23 Page 115 – I'm somewhat surprised by the increase in net pumpage associated with center pivots. Is it that more is lost to evaporation with this method?

H1-24 Page 116 – I'm a little uneasy with using the term equilibrium in this sense. In ture equilibrium the forward and reverse reaction rates (recharge and discharge as applied to groundwater systems) are always constant and equal. In systems at near steady state, changes in recharge will lead to changes in discharge and/or storage but the effects of the recharge stress plays out over time. Maybe I'm being to picky but I would prefer to refer to such systems as being in a quasi steady state.

H1-25 Page 118, sentences 1- Caveat: 'If T values are sufficiently large and the pumping rate is relatively constant ....'

H1-26 Page 155, sentences 6-8 – Don't know if you can say this with a great degree of confidence. There are also examples in figure 81 that show an upturn in precipitation that did not herald a 'significant' wet period. Examples include 1950-1955, 1980-1985, and 1990-1997.

H1-27 Page 156, figure 82 – Needs some units on the x and y axis.

H1-28 Appendix B – Need to specifically label shaded areas in the figures as representing the Bronenweld and Baugh estimates.

General comments:

H1-29 In almost every scenario, inflow from New Mexico exceeds the estimate of recharge of 35,000 acre-feet per year to the Salt Basin of Livingston and Shomaker (2002) in their 40-year planning document. I understand the approximate nature of model boundaries but still somebody is going to notice this.

Is it within the scope of your report to address this apparent contradiction? Is it within the scope of this report to discuss a scenario in which pumpage on the New Mexico side of the Salt Basin may increase substantially one day?

The report would benefit from a brief conclusions section bringing together the basic conclusions reached during formulation of this model.

Congratulations. This is a very nice piece of work.

G.F. Huff, Ph.D., PG

Huff HydroResources

Cited References:

Eastoe, C.J. and Hibbs, B.J., 2005, Stable and radiogenic isotope evidence relating to regional groundwater flow systems originating in the High Sacramento Mountains, New Mexico: EOS Transactions 86(52), Fall Meeting Supplemental, Abstract H33G-04.

Huntoon, P.W., 1995, Is it appropriate to apply porous media groundwater circulation models to a karstic aquifer, in El-Kadi, A.I., Groundwater Models for Resources Analysis and Management: Lewis Publishers, Boca Raton, Florida, p. 339-358.

Livingston Associates and John Shomaker and Associates, 2002, Tularosa Basin and Salt Basin regional water plan 2000-2040: South Central Mountain RC&D Council: Carrizozo, New Mexico, vols. 1 and 2, variously paged. (Available at http://www.ose.state.nm.us/isc_regional_plans5.html)

Looney, S.W. and Gulledge, T.R., 1995, Use of correlation coefficient with probability plots: The American Statistician, v. 39, p. 75-79.

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June 6, 2008

William R. Hutchison, P.H., P.E. P.G.
Water Resource Manager
El Paso Water Utilities
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1154 Hawkins Blvd.
El Paso, Texas 79925

RE: Peer review of the report titled *Preliminary Groundwater Flow Model, Dell City Area, Hudspeth and Culberson Counties, Texas*

Dear Bill:

Thanks for the opportunity to provide a peer review of your draft report titled *Preliminary Groundwater Flow Model, Dell City Area, Hudspeth and Culberson Counties, Texas*. I have reviewed the hard copy of the report and digital model files that were provided March 18, 2008.

Overall, the report provides a comprehensive overview of the groundwater system that encompasses Salt Basin (New Mexico portion), Dell City area, and Diablo Plateau. The report is well organized, and appears to contain all of the elements recommended by the Texas Water Development Board (TWDB) Groundwater Availability Model (GAM) program. To date, the report is the best overview of the groundwater conditions beneath Dell City/Diablo Plateau area, and the model will be a useful tool for managing groundwater resources of the area.

I provided hard copies of several references on the New Mexico side of the Salt Basin that would add to Section 3.0 "Previous Work." There are several key references that will help support the overall results of the model simulated water budget.

COMMENTS

The comments provided herein are mostly related to the conceptual model, particularly recharge, water level response, and the disadvantages of representing the entire model domain as one layer.

The comments are organized into three sections with suggestions related to: 1) report edits, 2) the hydrogeologic setting and conceptual model, and 3) ground-water flow model development, calibration, and results.

Suggested Report Edits

F1 1. Page 1, Figure 1 inset needs lat-long coordinates for reference

F2 2. Page 33, Figure 23 is labeled as Figure 2314

F3 3. Page 37, Table 8, 6th column to the right, should be "apparent transmissivity" instead of specific capacity.

F4 4. Page 39, Table 9 is listed as Table 29.

F5 5. Figures 28 through 30. It may be beneficial to list description and the extent (mi^2) for each Zone. This would help the reader understand the differences between models.

F6 6. Table s 18 through 20d. Listing the units would be helpful. I believe these numbers are in ac-ft/yr.

7. Pages 62 through 73, Tables with pumping data need to show units (ac-ft/yr, gpm, ft3/d?). Also, Tables 22a through 24b need units listed.

F7 8. Figure 47 title should be reworded to state Appendix C

F8 9. Table 48 under Pumping Scenario Code P3 the description has the word duties misspelled.

F9 10. Figure 103 needs to reference the 50-year period for drawdown. Page 176, 1st sentence should say "groundwater pumping vs. total drawdown" instead of average drawdown. Same for page 177 and Figure 104, and Page 178.

Hydrogeologic Setting and Conceptual Model

F10 1. Page 11, 3rd paragraph states "important aquifers in the area..." Using the term aquifers implies the geologic units are not hydraulically connected. I would prefer groundwater bearing units, hydrostratigraphic units, or geologic units. As you mention later many of these geologic units have different hydraulic properties, but are hydraulically connected.

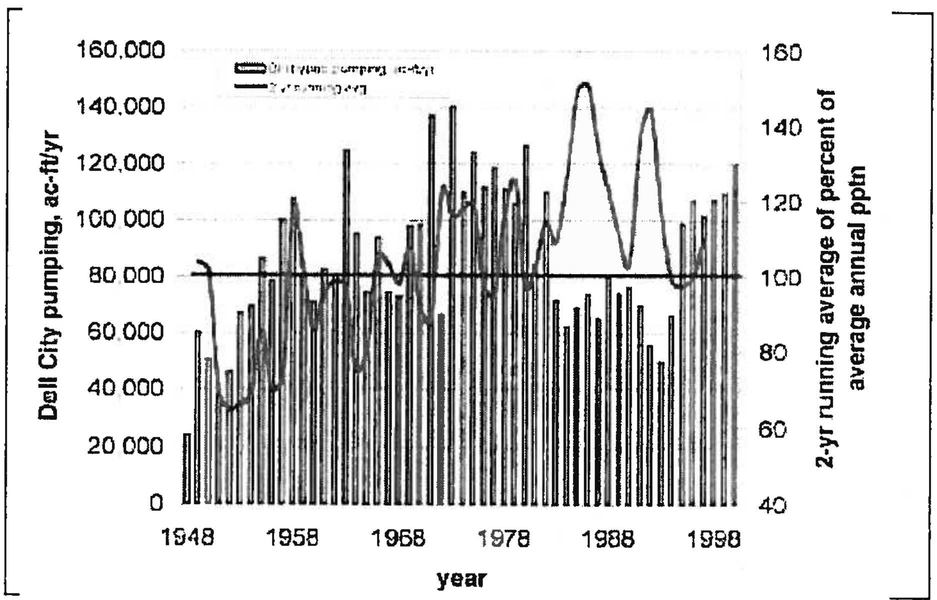
F11 2. Page 15, Review of Ashworth (1995). It is not mentioned in report. but can be deemed from data tables is the increased diversion crop irrigation requirement because of dissolved salt content in irrigation returns. Also, the pumping estimate is diversion and not consumptive use?

F12 3. Section 3.1.5 Huff and Chase (2006). The most important information in the work by Huff and Chase (2006) is the water level data presented on figure 9. The data could be used to support model calibration.

F13 4. Section 4.3 should discuss observed rate of water level decline and how that implies groundwater mining from storage. The changes in ground water levels are largely due to changes in pumping and recharge rates.

F14 5. Page 34, Table 7, you may wish to add the results from modeling efforts by Finch (2002).

F15 6. Page 35, 2nd paragraph. The hydrograph response could be from a decrease in pumping and increase in recharge for the 1985 to 1995 period and not a "new dynamic equilibrium." See graph below constructed from data in your Peer Review Draft report.



7. Page 36, Section 4.5. There are data available for Alamo Spring (Cornudas Mtns) and Carrizo Spring in the Sacramento Mountains. Carrizo Spring is one of the primary water sources for the Community of Timberon. Also, there are data available for Sacramento River in the Tularosa Basin and Salt Basin Regional Water Plan (2002). The mean annual stream flow between 1984 and 1989 is 2,173 ac-ft/yr. Gauging data ranged between 2 and 13 CFS. [F15]

8. Page 40, Section 4.7 Playas Discharge. Any observed water level data in the area of playa discharge would complement the discussion about reduced discharge by evaporated from water level decline, and also provides information on potential depth to water in the playa prior to significant development. Also, what about evaporation from the water table in areas where the depth to water is near surface? [F17]

9. Section 4.8 Groundwater Pumping. Including water quality effects on diversion requirements (Comment No. 2) would be helpful. [F18]

10. Page 49 and Figure 26. The well ID is mixed up in the text and on Figure 26., the Shallow well is 48-07-501 and the Deep well is 48-07-505. It would be helpful to discuss the thickness of aquifer tapped by the paired wells (Shallow and Deep) in addition to the total depth. In reference to the first paragraph, 3rd sentence, where is the thickness of the aquifer (1,000 to 2,000 ft) defined? The transmissivity is considered reasonably constant because the aquifer is thick (1,000 to 2,000 ft) and the historical drawdown of 50 ft is small compared to the thickness. The data shown on Table 8 indicates the upper few hundred feet has the highest hydraulic conductivity (transmissivity divided by portion of aquifer screened by well) and it decreases with respect to depth. If the hydraulic conductivity decreases with respect to depth, the transmissivity will significantly decrease with water level declines. [F19]

11. Page 51, Section 5.3.1. Groundwater flow across the northern watershed boundary from the Penasco Basin has been documented by Finch (2002). [F20]

Ground-Water Flow Model Development, Calibration, and Results

1. Page 55, Section 6.3.3. First paragraph states the LAYTYP is set to zero having constant transmissivity. Maintaining constant transmissivity for the model layer may under predict long term drawdown effects from reduced transmissivity. This may also reduce the amount of water pumped from storage and overstate the amount of pumping offset by salvaged evaporation. It may be beneficial to see if LAYTYP three for the model layer creates greater drawdown results. [F21]

2. Page 55, First sentence states the bottom of the model domain is 1,000 ft below land surface elevation. In many places along the model margin, Diablo Plateau, and in the northern model domain the depth to water is greater than 500 ft. Simulating a thin saturated zone along the model domain in recharge areas may require higher transmissivity than expected for the rock type. [F22]

F23 3. Page 55, 2nd to last paragraph. It may help the reader to explain why the zonation of hydraulic properties differ in the three models.

4. Figures 28, 29, and 30. A specific storage greater than $1x10^{-5}$ appears high for fractured rock. A discussion on assigned storage properties would be beneficial. A simple discussion on the three conceptual model zones would be helpful to the reader. For example, it appears all of the zones cover the same area except Zones 1, 7, and 9. F24

5. Page 85, Section 6.3.10. The ground-water divide in the Salt Bolson near the flexures appears to be evident from water levels in the bolson, but water levels in the Capitan Reef suggests continuous flow through the flexures. The difference in head between the bolson and Capitan Reef aquifer separates more saline water around the salt flats from the fresher Capitan Reef water (see Finch and Bennett, 2002). F25

F26 6. Section 7.1. There are not many calibration points between 5,000 and 7,500 ft elevation. It may be beneficial to show the calibration statistics for heads less than 5,000 ft elevation, which is the most important part of the model.

F27 7. Section 7.3. The model may be very sensitive to estimates of storage coefficients. A section describing a sensitivity analysis of storage coefficients may strengthen the parameters selected.

8. Section 8.4. It may be beneficial to discuss the results of a scenario with increased pumping during the driest conditions. It is likely the case that pumping will increase with drought and decrease with above average precipitation. Table 50 implies higher precipitation equals greater pumping. F28

SUMMARY AND RECOMMENDATIONS

Overall, the report describes previous work and hydrogeologic setting in good detail. Incorporation of the work performed in the upper portion of the model domain (reference materials were provided by mail) would strengthen the document.

The model is well documented and boundary conditions selected are reasonable. Some recommendations for future model updates are as follows:

F29 1. Perform sensitivity analysis with storage and Kh variations.

F30 2. Test the validity of the LAYTYP zero and constant transmissivity by performing a model run with LAYTYP three (variable transmissivity).

F31 3. Consider multilayer model although the calibration appears very good for the available data. A multilayer model would allow for decreasing hydraulic conductivity with depth, and variation in storage coefficient with depth.

F32 4. Variable recharge is great, although future model modifications may consider recharge from storm water runoff along major drainages.

F23 Section 8.0, Simulation of Potential Future Conditions, provides a lot of good analysis on water budgets and drawdown effects for a multitude of conditions. The one scenario missing is increased pumping due to the driest conditions.

Please let me know if you have any questions regarding my review comments.

Sincerely,

JOHN SHOMAKER & ASSOCIATES, INC.

Steven T. Finch, Jr.
V.P., Senior Hydrogeologist-Geochemist

STF:sf

Initial review comments on the report "Preliminary Groundwater Flow Model Dell City Area, Hudspeth and Culberson Counties, Texas" by William R. Hutchison, Ph.D., P.E., P.G.

Robert E. Mace. Ph.D., P.G.
Texas Water Development Board
June 9, 2008

Below are my initial comments and questions on the Hutchison (2008) report. an impressive effort, especially with respect to the testing of three different conceptual models and the quality of the final calibrations.

M1 • p. 34, Table 7: Consider including Blair's estimate of recharge (with and without return flows).

M2 • p. 34, Table 7: I have a vague recollection of Steve Finch doing a study of recharge in the Salt Basin using Maxey-Eakin in a report done for one of the groundwater conservation districts in Far West Texas.

M3 • p. 36, Section 4.6 Hydraulic Properties: Need a discussion of storage parameter data for the area or, if there is no data, presumptions on what the storage values might be.

M4 • p. 36, Section 4.6 Hydraulic Properties: Consider introducing the concept of the scale effect here.

M5 • p. 50, Section 5.3 Groundwater Movement: Nice touch to look at three different conceptual models—warranted given the Eastoe and Hibbs (2005) work.

M6 • p. 53, Section 6.1 Model Overview and Domain: It's unclear why you chose not to follow the watershed boundary for parts of the model and to follow it in others.

M7 • p. 57, Figure 28: Why is the hydraulic conductivity and transmissivity in Zone 8 so high? Is this geologically reasonable?

M8 • p. 74, Section 6.3.5 Drain (DRN) Package: Why didn't you choose to follow a flow line here so you could have a "no-flow" boundary?

M9 • p. 76, Figure 34: Related to an earlier comment concerning why you chopped off the water shed here where you could have avoided a general head boundary.

M10 • p. 77: Neat way to try and build in flow delay.

M11 • p. 85, Section 6.3.9 Horizontal Flow Barrier (HFB) Package: Seems odd to employ the HFB here. My conceptual understanding of water levels in this area is that the higher water levels (in the Cretaceous rocks) represent a perched system while there are much lower water levels in the Permian rocks underneath. Why didn't you just represent the Permian aquifer in the model and include the effect of the Cretaceous rocks through recharge.

M12 • starting on p. 100, modeled v. measured cross plots: It would be helpful to see a close up of the cross plot between 3,500 and 4,000 feet.

M13 • starting on p. 108 and in appendix. hydrographs: Real nice fits!

M14 • starting with Section 7.3.2. water budgets: Unclear why you are showing water budgets for different aquifer and district boundaries.

M15 • General comment: Does this model do a good job of representing the Capitan Reef Complex Aquifer? Seems like the model may be too simple to represent flow over

[M15] there. One of our researchers believes there may be flow from that area to the south and eventually over to San Solomon Springs.

Hutchison, W.R., 2005, Preliminary groundwater flow model Dell City area, Hudspeth and Culberson counties, Texas: El Paso Water Utilities, EPWU Hydrogeology Report 08-01, 351 p.

Huff HydroResources

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Date : June 25, 2008

To : William R. Hutchison, Ph.D., P.E., P.G.

From: G.F. Huff

Re: Final technical review of the report 'Preliminary groundwater flow model Dell City area, Hudspeth and Culberson Counties, Texas', EPWU Hydrology Report 08-01, in partial fulfillment of contract MCHUFFHYDROR08.

Bill,

I have reviewed the subject report and found it to be a very good piece of work. My comments are divided into those specific to a given part of the text or a selected figure and those of a more general nature. Your model represents a significant step forward in the quantitative representation of the hydrology of the Salt Basin.

Specific comments:

H2-1 Figure 4 – Location of the Guadalupe and Delaware Mountains should be shown on figure 4.

H2-2 Page 7 – The last sentence in section 2.1 should be moved to be the first sentence on page 6.

H2-3 Page 14 – Sentence starting with 'Reed (1965, pg. 18)' includes the text 'recharge to the area above a depth of 700 feet'. Not sure what this means.

H2-4 Page 15, section 3.6, second paragraph – 'flow down the structural dip of a monocline' is mentioned but there is no prior discussion of this monocline. Sentence needs some context.

H2-5 Page 24, figure 14 – The symbols on this figure are difficult to differentiate. If it's a copy of an original from Eastoe and Hibbs (2005) we may be stuck with it. However, if you generated the figure yourself you may want to consider using a greater variety of symbols. Also, axes need to be labeled with units of per mil (o oo).

H2-6 Page 33, section 4.4, paragraph 2 – Some things to consider in this paragraph. WhileDell City water could be explained by relatively unevaporated Diablo Plateau water it is not

dissimilar to Sacramento Mountains water as shown in figure 14. While water in the Dell City area certainly could have a Diablo Plateau component there also may be alternate explanations such as the possibility that runoff from summer rainfall on the Diablo Plateau may reach the Dell Valley area via surface runoff and infiltrate there. I'm a bit
F2-6 bothered by the fact that the Dell City area water doesn't show more of an evaporation trend on fig. 14 than it does considering that the Eastoe and Hibbs (2005) abstract states that the Dell City sample were taken from 'basin fill'. Do they mean the limestone aquifer or the alluvium covering the limestone aquifer in Crow Flats/Dell Valley? Page 36, sentence 1 – You may want to qualify return flow as 'current or modern' here as I am assuming a 2002 study would primarily discuss return flow as a fraction of irrigation applied using sprinkler systems rather than flood irrigation.

F2-7 Page 36, section 4.6, paragraph 1, sentence 1 – 'Hydraulic properties of the aquifer are parameters that describe the rate of movement and storage properties of the aquifer.'

F2-8 Page 36, section 4.6, paragraph 1, sentence 5 – Replace 'flow rate' with 'flux'.

F2-9 Page 36, section 4.6, paragraph 2, sentences 2-4 – Heterogeneity means that aquifer properties vary spatially.

F2-10 Page 41, section 4.8 – Were the Blair estimates of return flow based on the assumption of sprinkler irrigation, flood irrigation, or some combination of the two?

F2-11 Page 50, section 5.2, paragraph 5 – Is the table 29 referenced here actually table 9. While the observations of Huntoon (1995) may be correct is there not also a bias in the other direction in that most tested wells wind up being 'good' wells that are located in highly conductive parts of the aquifer?

F2-12 Page 53, figure 27 – Would it be worthwhile to have a figure actually showing the model grid?

F2-13 Page 53, section 6.1, paragraph 2 – I assume the model rotation was to align the grid with the regional trend in anisotropy. Is so, consider a sentence to explicitly state the reason for the model rotation.

F2-14 Page 60, paragraphs 4 and 5 and page 61, paragraph 1 – Identify 'zones' as 'irrigation pumping zones'.

F2-15 Page 75, section 6.3.6 – Specify Groenveld and Baugh estimate to be an estimate of ET under 2002 conditions if applicable.

F2-16 Page 88, sentences 1-3 – One of these 'western' boundaries needs to be an 'eastern' boundary.

H2-17 Page 99, paragraph 1 – Include some variation of this paragraph in an earlier part of the report. This explains a lot about questions I originally had on pages 74-78 on things like how T values at boundary heads were determined and why they varied between models and why something as apparently fundamental as cell elevation varied between the three models.

H2-18 Section 7.1 starting on page 99 – In order to use standard deviation in this sense you need to demonstrate that you cannot reject the null hypothesis of a normal distribution of residual errors. For a quick and powerful test for normality see Looney and Gulledge (1995).

H2-19 Also, a figure showing the spatial distribution of steady state residual errors would be useful. [Note: This looks like a very solid calibration.]

H2-20 Page 116 – I'm a little uneasy with using the term equilibrium in this sense. In true equilibrium the forward and reverse reaction rates (recharge and discharge as applied to groundwater systems) are always constant and equal. In systems at near steady state changes in recharge will lead to changes in discharge and/or storage but the effects of the recharge stress plays out over time. Maybe I'm being to picky but I would prefer to refer to such systems as being in a quasi steady state.

H2-21 Page 118, sentences 1- Caveat: 'If T values are sufficiently large and the pumping rate is relatively constant ....'

H2-22 Page 155, sentences 6-8 – Don't know if you can say this with a great degree of confidence. There are also examples in figure 81 that show an upturn in precipitation that did not herald a 'significant' wet period. Examples include 1950-1955, 1980-1985, and 1990-1997.

H2-23 Page 156, figure 82 – Needs some units on the x and y axis.

H2-24 Appendix B – Need to specifically label shaded areas in the figures as representing the Bronenveld and Baugh estimates.

General comments:

H2-25 In almost every scenario, inflow from New Mexico exceeds the estimate of recharge of 35,000 acre-feet per year to the Salt Basin of Livingston and Shomaker (2002) in their 40-year planning document. I understand the approximate nature of model boundaries but still somebody is going to notice this.

H2-26 Is it within the scope of your report to address this apparent contradiction? Is it within the scope of this report to discuss a scenario in which pumpage on the New Mexico side of the Salt Basin may increase substantially one day?

H2-27 The report would benefit from a brief conclusions section bringing together the basic conclusions reached during formulation of this model.

Congratulations. This is a very nice piece of work.

G.F. Huff, Ph.D., PG

Huff HydroResources

Cited References:

Eastoe, C.J. and Hibbs, B.J., 2005, Stable and radiogenic isotope evidence relating to regional groundwater flow systems originating in the High Sacramento Mountains, New Mexico: EOS Transactions 86(52), Fall Meeting Supplemental, Abstract H33G-04.

Huntoon, P.W., 1995, Is it appropriate to apply porous media groundwater circulation models to a karstic aquifer, in El-Kadi, A.I., Groundwater Models for Resources Analysis and Management: Lewis Publishers, Boca Raton, Florida, p. 339-358.

Livingston Associates and John Shomaker and Associates, 2002, Tularosa Basin and Salt Basin regional water plan 2000-2040: South Central Mountain RC&D Council: Carrizozo, New Mexico, vols. 1 and 2, variously paged. (Available at http://www.ose.state.nm.us/isc_regional_plans5.html)

Looney, S.W. and Gulledge, T.R., 1995, Use of correlation coefficient with probability plots: The American Statistician, v. 39, p. 75-79.

Responses to Comments

Rick Huff Comments dated April 11, 2008

H1-1. Locations of Guadalupe and Delaware Mountains added to figure.

H1-2. Suggested edit made.

H1-3. Sentence was edited to state that this was based on a Darcian calculation, hence the depth limit of the estimate.

H1-4. Removed reference to monocline.

H1-5. Unfortunately, this is the best that we can use.

H1-6. I agree that the origin of the water could be subject to alternative interpretations that I am sure Chris Eastoe will consider as he refines his analysis for publication. However, what is clear is that there is some difference in Texas and New Mexico that, at least, opens up the possibility that Diablo Plateau water is moving towards Dell City. The possibility of alternative explanations is one of the reasons that I carried all three models through calibration and used all three in future simulations. The model is also helpful in establishing that the movement of Diablo Plateau water may be accelerated though Dell City pumping.

H1-7. Clarification added.

H1-8. This was an admittedly poorly worded sentence that has been corrected.

H1-9. Suggested edit made.

H1-10. Clarification added.

H1-11. Clarification regarding sprinkler irrigation made.

H1-12. Table number corrected.

H1-13. Model grid for the HCUWCD area added. Full grid figure is not really readable given the large area and small grid spacing.

H1-14. Yes. Grid rotation was to align with the fracture system. Clarification added.

H1-15. Irrigation zone designation added.

H1-16. Area represents maximum ET area as defined by Groeneveld and Baugh. Clarification added.

H1-17. Boundary conductance values are in ft^2/day as defined in MODFLOW documentation.

H1-18. Steady state recharge was based on 100% precipitation. Clarification in text made.
H1-19. Eastern and western confusion corrected.

H1-20. Suggested clarification added.

H1-21. New section (7.1.3) added to deal with issue of normally distributed residuals and several new graphs added that are useful in evaluating spatial and temporal distribution of residuals.

H1-22. There are only about 5 data points in 1948, and all of them are in a small area. A "steady-state" calibration was not really attempted since the main purpose of the steady state stress period was to assure the initial head distribution at the beginning of the transient simulation was stable.

H1-23. The interpretation of increases in net pumping after 1993 is coincident with the general preference in center pivot systems. However, it is not possible to go deeper than making the observation (e.g. increased evaporation as suggested by the comment) because the model has no ability to simulate total pumping.

H1-24. "Near steady-state" is now used rather than equilibrium.

H1-25. Suggested caveat added.

H1-26. The discussion has been clarified. The intent was to discuss the 50-year average trends over a 1,000 year period. The comment is focused on the observed history of the last 50 to 60 years. I appreciated the comment since it clearly showed I had not made the time scale of the discussion clear.

H1-27. Correction made.

H1-28. Suggested clarifying note added to all figures in Appendix

H1-29. Discussion of Livingston Associates and John Shomaker & Associated (2002) added.

Steve Finch Comments Dated June 6, 2008

F1. Latitude and longitude tick marks added to figure.

F2. Figure number corrected.

F3. Table clarified and now contains specific capcity in three units.

F4. Table number corrected.

F5. Area of zones added to each table.

F6. Units added to all tables.

F7. Figure title corrected.

F8. Spelling corrected.

F9. Suggested clarification made.

F10. Connotation of non-connected units clarified.

F11. Suggested clarifications made.

F12. After discussion at our meeting of June 18, 2008, Huff and Chace contour map added and significance of Figure 9 added. The figure was not suitable to reproduce and Rick Huff could not locate the original data that were used for Figure 9 without a great deal of work.

F13. I agree that this is an important discussion. However, this is a difficult place to include it. I did, however, add a discussion about this observation and its significance in the discussion of results of the simulations.

F14. Results of Finch (2002) added to table.

F15. As with comment F13, I added a discussion about this observation and its significance in the discussion of results of the simulations.

F16. Summary of data added.

F17. Added a summary of observed groundwater elevation changes near the margins of the playa. The data were too sparse to present hydrographs.

F18. Suggested discussion added.

F19. Well numbers corrected.

F20. Discussion added.

F21. Discussion as to potential error added.

F22. Discussion as to limitation/error added.

F23. Zonation is different as a means to implement the three conceptual models.

F24. Unfortunately, there is virtually no data on storativity. A discussion of the differences in zonation was added.

F25. I agree.

F26. An entire subsection dealing with calibration graphics and statistics in the Dell City area was added.

F27. The sensitivity of storativity is discussed in Section 8.5, specifically Figures 139 and 140.

F28. The highest pumping scenario is P3, the driest scenario is C1. Simulations 43, 44 and 45 are the three simulations (one for each model) under highest pumping and driest climate scenarios.

F29. Storativity sensitivity is covered in Figure 137 and 138.

F30. This is a preliminary model and the potential errors and limitations associated with LAYTYP zero are discussed.

F31. A multilayer model would work better in the Capitan area especially.

F32. I agree that more definition of the spatial and temporal distribution of recharge would be good, especially if the stress periods were less than annual, and if the objectives of the model warranted the complexity.

F33. As noted in the response to F28, the highest pumping/driest climate scenarios are 43, 44 and 45. There is no detailed discussion of these since there is no need to elevate their status above other scenarios. The overall distribution is the focus, not a "worst-case" analysis.

Robert Mace Comments Dated June 9, 2008

M1. Suggested clarification made.

M2. Yes. Steve's report was made available after the Peer Review Draft was released. Steve was kind enough to send me a copy. A summary of the report has been added.

M3. Brief discussion of storativity data (or lack thereof) was added.

M4. Suggested additional discussion added.

M5. Thank you.

M6. Suggested discussion added.

M7. Suggested discussion added.

M8. Discussion added to clarify the approach taken.

M9. Suggested discussion added.

M10. Thank you.

M11. Discussion (and diagram) added to clarify the approach taken.

M12. An entire section on the statistics and graphics associated with the calibration of the model in the Dell City area was added.

M13. Thank you.

M14. As stated in the text, this was a means to evaluate different areas and demonstrate that the water budget components change with different areas. It was also done, as described, to facilitate comparisons to previous studies.

M15. The main focus was Dell City. The models are reasonable with respect to the Capitan, but not as reliable as Dell City area. I have added some discussion regarding this.

Rick Huff Comments Dated June 25, 2008

Rick Huff resubmitted his comments after the meeting of June 18, 2008. Most of them are repeats of his earlier letter as noted below.

H2-1. Same as H1-1

H2-2. Same as H1-2

H2-3. Same as H1-3

H2-4. Same as H1-4.

H2-5. Same as H1-5.

H2-6. Same as H1-6.

H2-7. Same as H1-8.

H2-8. Same as H1-9.

H2-9. Same as H1-10.

H2-10. Same as H1-11.

H2-11. Same as H1-12.

H2-12. Same as H1-13.

H2-13. Same as H1-14.

H2-14. Same as H1-15.

H2-15. Same as H1-16.

H2-16. Same as H1-19.

H2-17. Same as H1-20.

H2-18. Same as H1-21.

H2-19. Same as H1-22.

H2-20. Same as H1-24.

H2-21. Same as H1-25.

H2-22. Same as H1-26.

H2-23. Same as H1-27.

H2-24. Same as H1-28.

H2-25. Same as H1-29.

H2-26. Same as H1-29.

H2-27. Conclusion section added.